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Experimental investigation of the factors affecting the burning rate of solid rocket propellants

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HIGHLIGHTS

- Burning rate in a rocket motor is an important factor determining the rocket performance.
- Burning rate is the most important design criteria for the solid propellant rockets.
- Initial temperature of the solid propellants affects the working performance of the rocket.
- Adding Al into the ingredient of DB propellant increases the burning rate and energy.
- The results based on DB ingredients adding Al shows similarities with the literature.

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ABSTRACT

The burning rate of the solid rocket propellants is one of the most important factors that determine the performance of the rocket. The burning rate of rocket motors running with solid propellant is called flame regression, which occurs with the ignition in the fuel grain perpendicular to the burning surface. This study investigates the effects of the addition of metal-based high-energy matter (Aluminum) into the content of the propellant produced within the scope of development project. The study starts with the manufacture of propellant samples. For the data input in the burning rate measurement device, the determination process of energy levels of the manufactured propellant samples with a calorimeter is performed. Then, the other data related to the propellants to be measured for the burning rate, such as energy level of the propellant, the propellant density, the maximum combustion temperature, and the physical sizes of the propellants, were inputted to the computer of the burning rate measurement device. The 22 g of the sample propellant to be measured for burning rate was placed in a part of the burning rate measurement device, "closed bomb" which has a capacity of 200 cm^3. Burning rate measurements were performed at the same time in a constant-volume environment under different pressures. The burning rate of the double base propellant without aluminum (DB-1) was compared with other double base fuels in which aluminum was added by 2% (DB-2) and 4% (DB-3). It was found that the burning rates and burning heat of new fuels manufactured by adding aluminum to the content of the standard double base fuel (DB-1) increased.

1. Introduction

One of the most important design criteria of rockets running with solid propellants is the burning rate of the solid propellant. For this reason, the burning rate of the propellant which will be used in rocket motor design initially must be known. The burning rate of a solid propellant is expressed as the regression of propellant perpendicularly from the center of the nucleus. The burning rate of the solid propellants varies depending on many factors, such as the combustion chamber pressure, the initial temperature of solid propellant before the ignition, the percentage of high-energy matters in the propellant content, the burn sensation of the flammable substance, the additional chemical substances regulating the burning rate, and the percentage of the amount of oxidizing agent.

Although the burning event of the solid rocket propellants is quite complex, its mathematical model is sufficiently established.

Abbreviations: DB, double base; NG, nitroglycerin; NC, nitrocellulose; CMDB, composite solid propellant; PbSa, lead salicylate; PbEH, lead two ethyl hexanoat; UT, ultrasonic burning rate measurement technique; SBT, strand burner burning rate measurement technique; AP, ammonium perchlorate; IPDI, isophorone diisocyanate cured; DEP, diethyl phthalate; NG, nitroglycerine; 2NDPA, 2Nitrodiphenylamine.

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Burning which starts from the nucleus in motors of the solid rocket propellant progresses in a direction perpendicular to the outside surface of the propellant. As the burning progresses perpendicularly, the viscosity of the propellant lessens. The amount of reduction in the thickness of the propellant per unit of time is expressed as the burning rate. In military applications and cabinet in space research, the rocket motor sends the warhead to the intended destination. In the design of the rocket engine, the specific impulse (I_{sp}), the burning rate (r), the propellant density (ρ_b), the combustion chamber pressure (P_c), the intended thrust force (F), the maximum engine pipe diameter (D), the burning surface area (A_b), the nozzle cross-sectional area (A_t), and the total mass of the engine should be determined carefully [1,2].

The mathematical representation of burning rate of solid rocket propellant and factors affecting burning rate is given by

$$\text{Linear Burning Rate} = \frac{\text{Solid Propellant (mm)}}{\text{Burning Duration (s)}} \tag{1}$$

$$r = \frac{dw}{dt} \tag{2}$$

The solid propellant burning rate equation known as Vielle's Law is

$$r = kP_c^n \tag{3}$$

The burning rate (r) essentially depends on the initial temperature of propellant and pressure of the combustion chamber. P_c combustion chamber pressure, k initial constant temperature of the solid and its value vary between 0.002 and 0.05, n which is called as the pressure index or pressure base is a function of the solid propellant formulation. In double base (DB) propellants, the value of n is between 0.2 and 0.5 and in AP (Ammonium Perchlorate) based composite fuels, the value of n is relatively lower, varying from 0.1 to 0.4 [4].

During development of a new or modified solid propellant, it is extensively or characterized. This includes the testing of the burning rate (in several different ways), under different temperatures, pressures, impurities, and conditions. Characterization also requires measurement of physical, chemical, manufacturing properties, ignitability, aging, sensitivity to various energy inputs or moisture absorption and compatibility with other materials. It is a lengthy, expensive, often hazardous program with many test, samples and analyses [9].

The burning rate of propellant in a motor is a function of many parameters and at any instant governs the mass flow rate $\dot{m}$ of hot gas generated and flowing from the motor (steady combustion):

$$\dot{m} = A_b r \rho_b \tag{4}$$

Here (A_b) is the burning the burning area of the propellant grain, (r) the burning rate, and (ρ_b) the solid propellant density prior to motor start. The total mass (m) of effective propellant burned can be determined by integrating equation:

$$m = \int \dot{m}dt = \rho_b \int A_b r dt \tag{5}$$

where (A_b) and (r) vary with time and pressure [9].

The initial temperature of solid propellant directly affects the combustion chamber pressure (P_c) and burning rate (r). This effect is expressed as the burning rate temperature sensitivity (Π_r) and the equation of burning rate change under constant pressure with different temperatures is as given below;

$$\Pi_r = \left[\frac{\partial r}{\partial T}\right]_{P_c} = \left[\frac{\partial \ln(r)}{\partial T}\right]_{P_c} = \left[\frac{\partial \ln(kP_c^n)}{\partial T}\right] = \frac{1}{k}\left[\frac{\partial k}{\partial T}\right]_{P_c} \tag{6}$$

The temperature sensitivity of the pressure (Π_P), burning surface and nozzle block section ratio in fixed conditions is expressed with the following equation [3,5];

$$\Pi_P = \frac{1}{P_c}\left[\frac{\partial P_c}{\partial T}\right]_{\frac{A_b}{A_t}} = \left[\frac{\partial \ln P_c}{\partial T}\right]_{\frac{A_b}{A_t}} \tag{7}$$

From the above equation;

$$\Pi_P = \frac{\partial \ln(P_c)}{\partial T} = \left(\frac{1}{1-n}\right)\frac{1}{k}\left[\frac{\partial k}{\partial T}\right] = \frac{\Pi_r}{1-n} \tag{8}$$

The equations of (1)–(8) given above correlate with the temperature, the pressure, and the burning rate.

There are many parameters affecting the burning rate in solid propellants. First is the combustion chamber pressure of rocket motor (Pc). The chemical structure of the propellant, the rate of propellant in the fuel, and particle size of propellant components are known as the effective structures on the burning rate of solid propellant. The initial temperature of solid rocket propellant before the ignition directly affects the burning rate, burning time, and internal engine pressure.

1.1. Burning in solid propellants

In motors running with solid propellant, the burning event is quite complex. The chemical and physical events happening during the burning are not fully understood. Burning models developed so far are still quite simplified. The flame structure, gaseous phases, and other products during the burning can only be demonstrated with mathematical models [2,6].

The burning rate in rocket motors running with solid propellants is expressed as a regression from the combustion surface in terms of time. As seen in Fig. 1, the burning rate of solid propellants can be accepted as the burning distance per unit of time. Generally, mm/s, cm/s and inch/s are used as the units of burning rate.

In DB fuels, burning happens without a need for oxygen due to the co-existence of propellant (NG and NC), which are fundamental components of DB fuels.

In composite solid propellants used in modern solid propellant rocket motors, AP, polymer-based binder, and powdered aluminum (Al, between 0% and 20% amount) are generally used as oxidizers [6]. The use of metallic fuel has a modulating effect on unsteady burning in low pressures. In addition, it is known to increase the specific impulse of rockets. But on the other hand, it decreases the temperatures and rates of burning products leaving the nozzle, due to the aluminum oxide formation. The mixing ratios of solid rocket propellants by weight in general are given in Table 1 below.

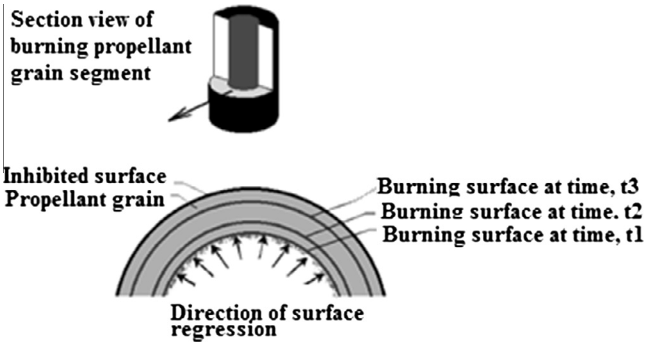

Fig. 1. Burning rate regression of solid propellant from the nucleus of the fuel to the outer surface of rocket motor in a perpendicular direction in terms of time [7].

1.2. Factors affecting the burning in solid propellants

In order to find the internal pressure of the rocket motor, it is necessary to determine the geometry of the nucleus of the propellant since the internal pressure of the motor depends on its burning area. As the solid fuel burns the burning area changes. For this reason, in order to estimate the motor pressure–time, each burning step of the burning area is needed. The analysis conducted for determining the burning area for each burning step is called "burnback analysis" [8].

Star-shaped structures are generally preferred for representing the nucleus of the solid propellant rocket motors despite the existence of other geometrical shapes. In star-shaped solid fuels, the burning surface area remains approximately ±15% constant during the burning. The remaining burning surface area helps the burning rate to progress smoothly, allowing the rocket to fly more stable, as seen in Fig. 2 in a star-shaped propellant nucleus.

The burning rate of solid rocket propellant is a function of propellant content. The content of propellant mixtures directly affects the burning rate. Factors that can change the burning rate are as follows:

- Addition of catalyst materials or new burning rate enhancer.
- Reduction of oxidizer particle size.
- Increase of the percentage of oxidizer agents.
- Increase of the amount of binder or oxidizer agent enhancing burning rate.
- Addition of metal rods or metal fibers into the fuel.

The effects of motor manufacturing conditions on the burning rate other than those of chemical composition of solid propellants are as follows;

- Combustion chamber pressure.
- Initial temperature of the propellant before the burning.
- Temperature of burning gas.
- The speed of gas flowing parallel to the burning surface.
- The motor movement (acceleration and turbulence regression within the nucleus)

The burning rate in solid rocket propellants behaves differently depending on various factors [2].

1.3. Effects of pressure on burning rate

The pressure increase in the combustion chamber is one of the most important factors increasing the burning rate. As seen in Fig. 3, as the pressure of the combustion chamber increases, the burning flame profile varies; flame size reduces and burns faster [10].

The burning behavior and rate of solid rocket propellants vary under different pressures. The burning rate increases along with an increase in combustion chamber pressure.

Table 1
Solid rocket propellant components by percentage (%) of weight; double base (DB), composite and composite modified double base components (CMDB) [2,10].

Additives	Double base (%)	Composite (%)	CMDB (%)
NC	51.5	–	21.9
Plastic-based binders	(NG) 43.0	(PBAA) 12.0	(NG) 29.0
Ballistic additives	3.2	–	–
Oxidizing (solid)	–	(AP) 70.00	(AP) 20.4
Metallic fuel (solid)	–	16.0	21.1
Stabilizers	2.3	–	2.5
Hardener	–	2.0	5.1

Fig. 2. Minimal burning model in star-shaped propellant nucleus [9].

Fig. 3 shows that burning rate increases parallel to the increase in pressures, as also seen in Table 2 below.

In this study, burning rates under different pressures [(A), (B), (C)] were seen to increase along with the increase of pressure as shown in Table 2.

1.4. Effects of initial fuel temperature on burning rate

The initial temperature of solid propellants is one of the factors which directly affects the working performance of the rocket. In rocket motors using composite fuel, a change of 25–35% in combustion chamber pressure and 20–30% in combustion duration can occur [4].

The relation between pressure–temperature and burning rate is shown in Fig. 4. It can be seen in Fig. 4 that as the initial temperature and pressure of the combustion chamber increase, so does the burning rate [16].

Combustion chamber pressure and combustion duration of initial temperature of the propellant before the burning are given in Fig. 5. As the temperature of propellant increases, the combustion end-pressure increases, the combustion duration shortens, and the specific impulse increases [4].

In Fig. 5, the comparison of combustion duration and pressure variations in three different initial temperatures (A: +27 °C, B: +50 °C, C: −40 °C) are shown. As the initial temperature increases, the rocket combustion chamber pressure increases and combustion duration shortens. As initial temperature decreases, combustion duration lengthens and combustion chamber pressure decreases.

1.5. Some other factors affecting the burning rate of solid propellant

Burning rates of solid rocket propellants are known to differ depending on various factors. In their experimental study in 2011, Xiong-Gang and his colleagues investigated the relation between the burning rate of solid propellant and the pressure on condition that all the initial temperatures of solid propellants are 293 K, as seen in Fig. 6. In their first experiment, they investigated the effect of combustion chamber pressure on burning rate with-

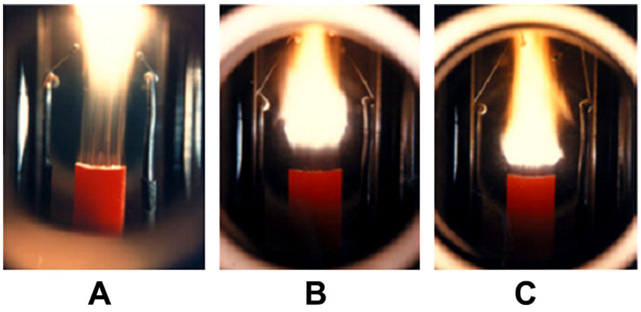

Fig. 3. Analysis of flame behavior and rate of double base (NG–NC) solid rocket propellant under different pressures [10].

Table 2
Effects of pressure on NG–NC double base rocket propellants [10].

Experiments	Pressure P (MPa)	Burning rate (mm/s)
A	1.0	2.2
B	2.0	3.1
C	3.0	4.0

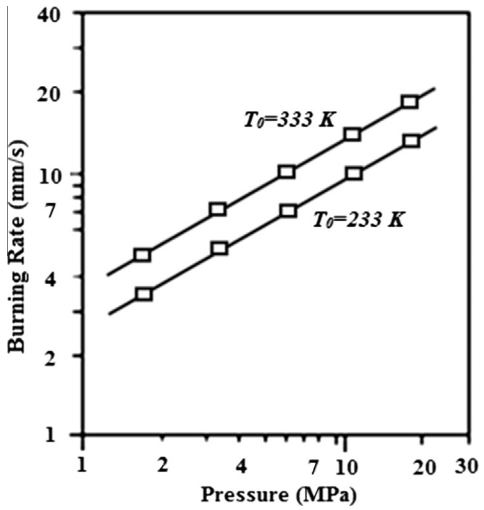

Fig. 4. The effect of initial temperature value of solid propellant on burning rate under different pressures [16].

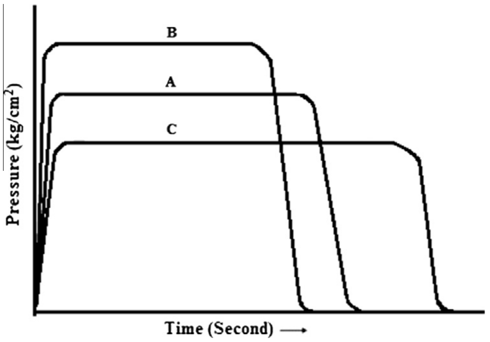

Fig. 5. Effect of initial temperature of propellant nucleus on burning rate and chamber pressure (A:+27 °C, B:+50 °C, C: −40 °C) [4].

out adding metal based high energy matters to the CMDB solid propellant. Then they investigated the burning rate behaviors under different pressure values by adding high energy metallic based matter into the solid propellant having the same properties. While looking at the effect of pressure on the burning rate of CMBD solid propellant without adding any metallic additives, they found that CMBD burns faster than other propellants, except for the boron-added fuel (B-CMBD) between 1 and 15 MPa pressure ranges. Between the ranges of 15–22 MPa, it was found that the burning rates of other high energy propellants with metallic additives are higher than those without any high energy fuel additives [11]. In pressures higher than 15 MPa, an increase was seen in the burning rates of all propellant samples having high energy metallic matter additions.

Fig. 7 shows the relation between burning rate-pressure and various aluminum additive particle sizes (nano and micron). As the powder size of metallic propellant gets smaller, the expansion of burning surface area increases, depending on the burning rate pressure.

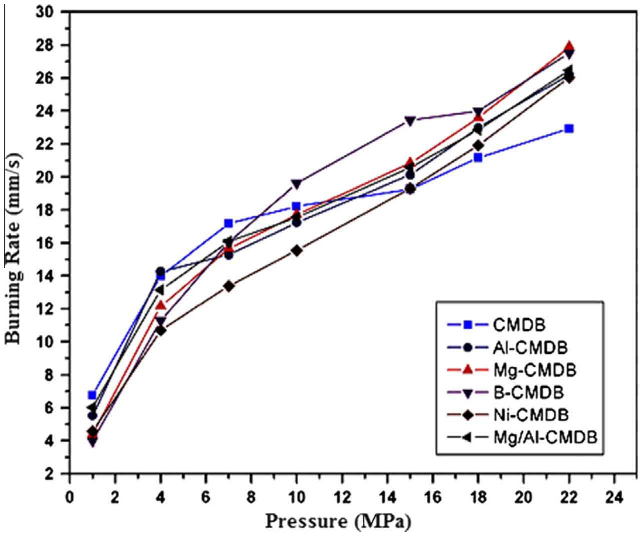

Fig. 6. Analysis of changes in burning rates depending on pressures between 1 and 22 MPa range on CMBD propellants including different high energy matters added fuels on condition that all the initial temperatures 293 K [11].

In their study conducted in 2009, K. Jayaraman and his colleagues investigated the effects on burning rate of the addition of different nano and micron sized Al into the content of composite base solid rocket propellant. In light of the results, it was determined that as the particle size and percentage amount increase, burning rate increases under various pressures due to the increase in burning surface area as seen in Fig. 8.

In order to increase the burning rate of double-based (DB) propellants, lead-based PbSa and PbEH are added [10].

Raising the energy levels of solid rocket propellants will increase the pressure and the temperature of the rocket motor combustion chamber. Depending on the increase in the pressure and temperature of the solid propellant, its burning rate will increase and the running conditions of rocket motor will improve.

The burning rates of three different double base (DB) solid propellants whose energy levels were made higher increased under 0.6 MPa, 1.1 MPa, 2.1 MPa and 3.4 MPa constant pressures, parallel with the increase in energy levels, as seen in Fig. 9.

In a study in 1996 conducted by Akçil, M., it was found that by adding 0–12% A1 with different percentage and particle sizes into the content of DB propellant, the burning temperature increases from 860 cal/g to 1135 cal/g [2]. In [2], the Al was added to the solid propellant ingredient but in the laboratory conditions as opposed to our work done by professional machine systems in a rocket solid propellant fabric. Moreover, our work measure not

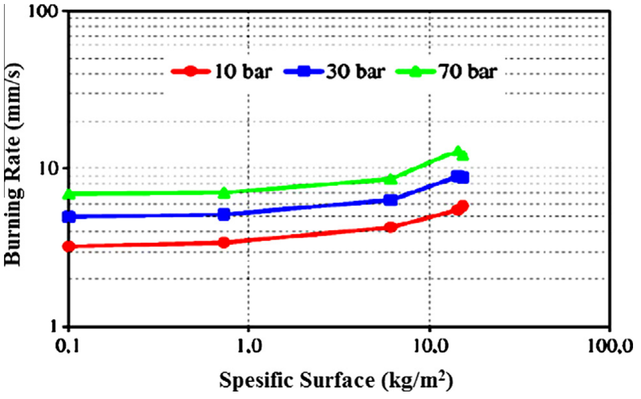

Fig. 7. Relations between burning rate, surface area and pressure [12,13].

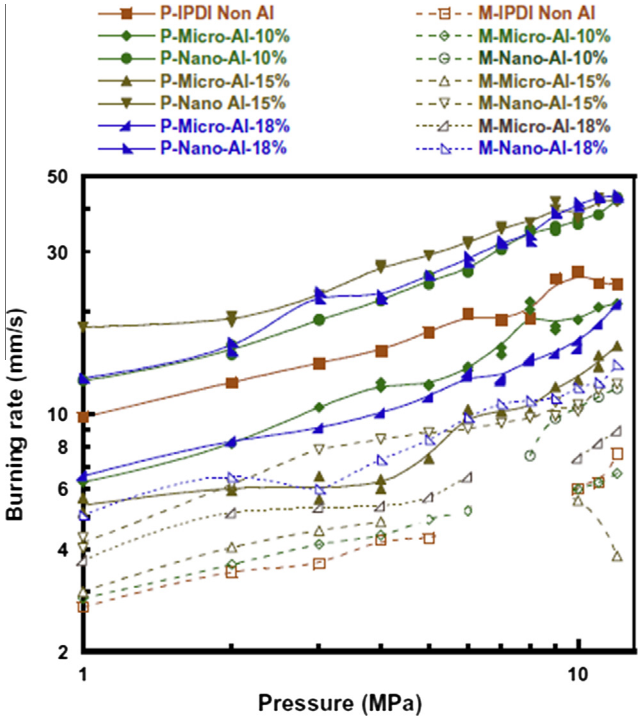

Fig. 8. Burning rate changes of propellants prepared with 65%/35% AP (5 μm) oxidizer binder percentage by adding different percentages of aluminum amount and particle size nano and micron with IPD cure method added to the content of composite base rocket propellants under different pressures [15].

only the burning rate but also the burning energy of the solid propellant.

2. Materials and methods

Burning rate is one of the important design parameters of rocket motors. It varies depending on factors of initial temperature of solid propellant, the temperature sensitivity coefficient of the propellant, the combustion chamber pressure, and the sensitivity of pressure coefficient exponent.

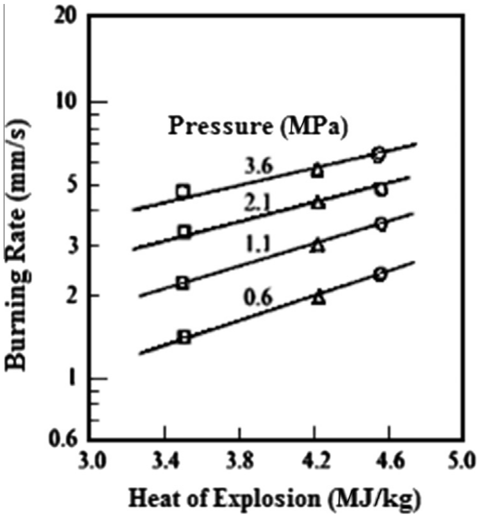

Fig. 9. Burning rate chart of three different double base (DB) solid propellants whose energy levels were increased under four different constant pressure [10].

Solid fuel burning rates have strong influences on the ballistic behaviors of rockets. For this reason, the accurate determination of the burning rates of solid rocket propellants is very important. Burning rates of solid propellants can be measured by using two methods. Standard method depends on burning rate measurement of the strand burner of solid propellant under predetermined fixed pressure of burning regression in nitrogen (N_2) environment. This method is costly and requires a long time. On the other hand, the ultrasonic method for measuring the burning rate depends on the data obtained at one shot constant volume burning from different pressure values and high-frequency sound waves.

2.1. Solid fuel burning rate measurement method in nitrogen environment by using strand burner

For the measurement of the burning rate, a strand burner is used. Since the burning of a strand burner produces additional burning gas in the burning environment under the nitrogen removal conditions, the pressure will increase. However, to ensure constant pressure during the measurement, a pressure valve added to the nitrogen (N_2) gas supplier automatically controls the flow ratio of nitrogen gas, allowing the reaching of the intended pressure conditions during the measurement, as shown in Fig. 10.

2.2. Solid fuel burning rate measurement with the method of high frequency ultrasonic wave and pressure change

Tests of the burning rates of solid rocket propellant are conducted using an ultrasonic technique. With this technique, the instantaneous measurement of the thickness of solid fuel is efficiently achieved. This technique was developed by ONERA (The French Aerospace Lab) in 1980s.

The ultrasonic technique uses the simultaneous flow of data related to the ultrasonic signal and pressure in large pressure ranges during the burning duration. In recent years, the ultrasonic wave technique has been recommended for the burning rate measurement of solid propellant, as shown in Fig. 11.

The fuel segment to be measured is attached firmly to the part which is the unit of ultrasonic measurement system defined as a “closed bomb.” The fuel is burned in the closed bomb with constant volume. The ultrasonic technique depends on the logic of measuring the solid fuel burning rate in a single shot by transferring high-frequency sound wave (ultrasonic) data occurring under

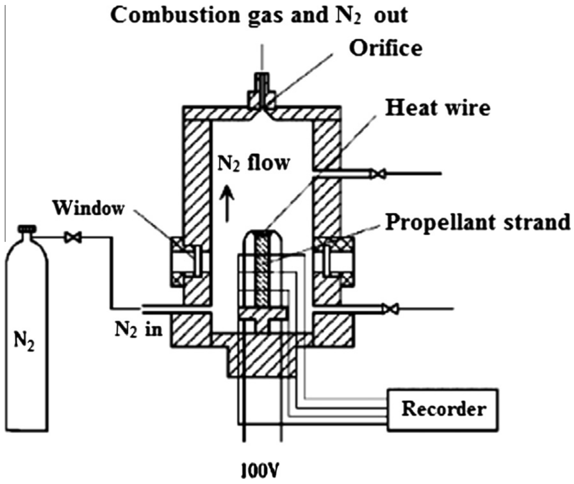

Fig. 10. Burning rate measurement system of solid propellant done by using Chimney-type burning observation strand burner in nitrogen environment [10].

all pressure changes throughout the burning duration into the computer with A/D (analog/digital) converters, as shown in Fig. 12.

In a study, Sung-Jin Song and his colleagues used both of the burning rate measurement methods of high-frequency sound (ultrasonic) and strand burner recession.

They measured fuel samples having composite AP-A1 and CMBD content. In their study, they compared propellant measurements of ultrasonic and strand burner methods on propellants having the same properties in the same chart. They obtained excellently compatible results in the measurements conducted with Ultrasonic (UT) and Strand Burner (SBT) methods and found a maximum 1.64% difference between the two methods under 70 MPa (1000PSI) pressure.

As seen in Fig. 13, they obtained similar results for the burning rates of CMBD propellants having the same properties with both UT and SBT methods [14]. When the two solid propellant burning rate measurement methods are compared, it was concluded that ultrasonic measurement method is advantageous since the results can be obtained more economically and in a shorter time.

2.3. Experimental sample solid propellants' production, testing and measuring methods

In this study, firstly the components of the propellants which will make the sample produces are determined. The mixtures are prepared to investigate the effects of aluminum addition in percentage of weight of the double base propellant (DB) component to the burning rate and the energy level of the propellant to be produced. In Table 5 below the components of DB-1, DB-2 and DB-3 are shown according to the percentage of weight.

The basic components of the double base (DB) propellant; nitroglycerine (NG) nitrocellulose (NC) other stabilizing and combining additions brought up to a liquidly consistency mixture in environment of 70 °C in hydrous mixing machine. The mixture which came out of the hydrous mixing machine in a liquid consistency were driven to the centrifuge machine and its water was extracted on average 1000 d/d in 30 min, for 7 days at 48 °C, the water extracted propellant sample component had a process of drying and losing damp. After the propellant sample mixtures had had a drying process, they had a grinding process, 2% was decreased of weight of the solid propellant component and by adding 10–20 μm size spherical Al with the same percentage instead, DB-2 propellant was prepared, from the spherical Al instead, solid propellant mixture was gained. DB-2 and DB-3 solid propellant components were mixed for 30 min in ex-proof mixing machine as seen in Fig. 14 in order to make homogeneous mixture of Al.

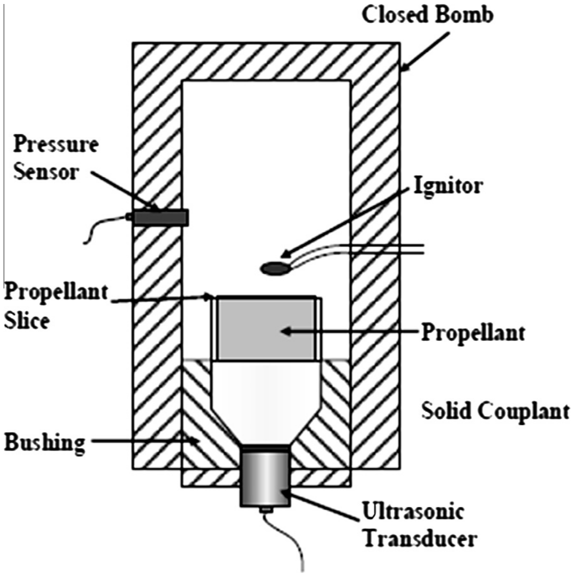

Fig. 12. Schematic view of closed bomb measuring and testing assembly of burning rate part of solid propellant sample [14].

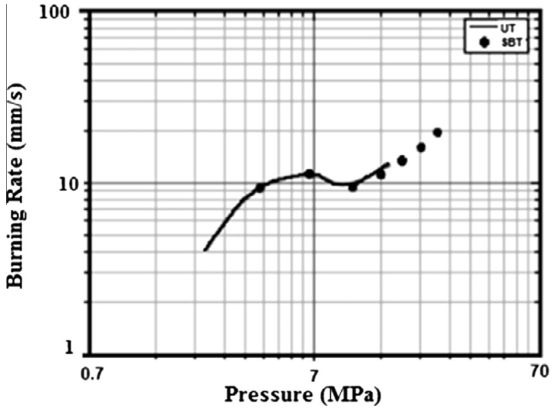

Fig. 13. Comparison of the burning rate results of ultrasonic and strand burner methods on composite modified double base (CMBD) propellant [14].

The propellant samples of which the homogeneous mixtures were gained from the ex-proof mixing machine were driven to the milling process. Milling process was realized in two steps, in

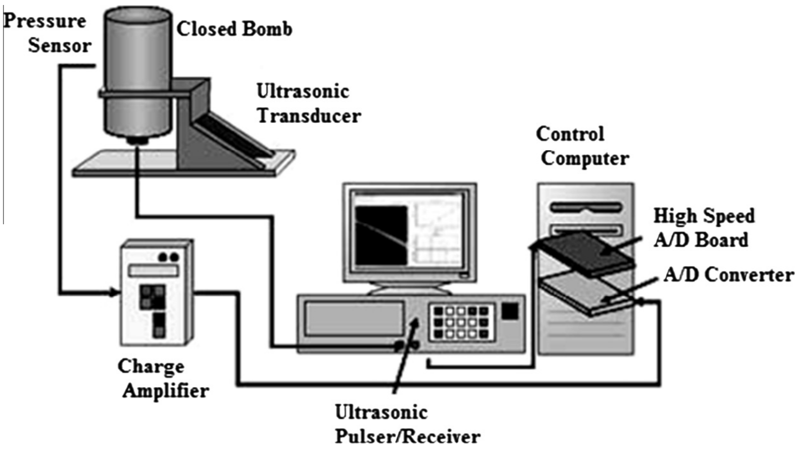

Fig. 11. Data analysis operating system of ultrasonic full-wave signal and pressure acoustic [14].

the same speed and different speed working machines. The rolling process under 110 °C made the solid propellant samples more homogeneous and more elastic. Besides, the solid propellants leaving the milling process could be brought up to a proper nucleus structure for the rocket engine tube by extrusion method.

The products DB-1, DB-2 and DB-3 solid propellant samples are shown in Fig. 15.

A DB-1 Al solid propellant without addition, B solid propellant with 2% addition, C solid propellant with 4% addition.

The burning rate of the sample solid propellants (DB-1, DB-2 and DB-3) were measured with Strand burner method in nitrogen gas environment under pressures of 10 MPa, 20 MPa, 30 MPa, 40 MPa, 50 MPa, 60 MPa,70 MPa, 80 MPa and 90 MPa.

Before beginning the second burning rate measurement the energy levels of the sample solid propellants were determined. The energy levels of DB-1, DB-2, DB-3 propellants were input to the burning rate measurement computer as data. After the sample propellants of which the burning rate wished to be measured had been conditioned at 18 °C (291 K) for 8 h, they were put into the closed bomb. So each sample solid propellants ‘burning rate was provided to be done at the same condition. The measurement system which was done in constant volume and different pressure is shown in Fig. 16 below.

Closed bomb constant volume and different pressure measurement at the pressure points of 10 MPa, 20 MPa, 30 MPa, 40 MPa, 50 MPa, 60 MPa, 70 MPa, 80 MPa and 90 MPa were input to the burning rate measurement computer. The measurements done with the Strand Burner method were compared to the burning rate of the sample propellants in constant volume. As a result the both measurements output were seen almost the same.

The densities of the sample of solid propellents are detected after the propellant produced. As seen in Fig. 17, the solid propellant samples are weighted within 0.0001 the sensitive rate. In the measurement of the air environment, the samples of the solid propellant are weighed with the degree of accuracy as 1 g, at constant temperature condition. These solid propellant samples are weighted not only in air environment but also in pure water environment. Water assisted weighing are fulfilled at constant 19 °C degrees. As shown in Fig. 17

Recall that the standard density equation is given by

$$\rho_b = \frac{m_A}{m_A - m_W} \times F \tag{9}$$

where (ρ_b) is the measured density of the solid propellant, (m_A) is the measured mass of solid propellant in air environment, (m_W) is the mass of solid propellant in the water environment and (F) is the pure water density on the temperature.

The density of the solid propellant is calculated using the Eq. (1). Besides, the density of each solid propellant samples is calculated separately, using (F) taken from the table as 0.099843 at the constant water temperature 19 °C degrees. Table 6 shows the density of the solid propellant samples.

3. Results and discussions

This study was done in order to increase the burning rate and the energy levels of the sample solid propellants in which DB content materials were mixed in different percentages of weight. Sample propellants were produced by using the determined percentages of weight of double based propellant components.

DB-1 component was prepared with a content as seen in Table 5 by using different weight of double base (DB) solid propellant components as can be seen in Table 2. DB-2 solid propellant component was produced by decreasing the weight of DB-1 component 2%, 2% Al content was added instead. DB-3 sample propellant was produced by decreasing DB-1 content 4%, spherical structured 10–20 μm size Al was added instead. The energy levels of the sample propellant products were measured and given in Table 3 here it was determined that when the amount of Al% was increased, the energy level of the solid propellant increased.

The results of the burning rate measurements done with the methods of Strand Burner and the constant volume close bomb were compared. When the both burning rate measurement methods were compared maximum 0.4% difference was found. The burning rates of the solid propellant samples measured with the method of constant volume closed bomb are given in Table 5.

The constant volume closed bomb burning rate measurement method was seen to be more economic and shorter in time.

After the production of propellant samples, their burning temperatures needed to be known in order to determine the burning rate of solid rocket propellant with constant volume (V = Constant) burning rate measurement method. For this reason, the energy levels of double base solid fuels produced in three different compositions were measured with a device which could measure 1 g for each sample. The measurement of energy levels of propellants with 1 gram unit volume mass was done precisely, as seen in Table 3. The measurements which were done with the calorimeter were performed twice and their averages were taken.

The burning temperature values of propellant samples measured as cal/g were converted into j/g by multiplying them with a coefficient of 4.18 and this data was entered into the burning rate device. As the percentage of A1 increases, so does the burning heat, as seen in Table 3. The burning heat of DB-3 increased by 3.78% when compared with DB-2. Burning rate of DB-3 increased by 8.21% when compared with DB-1.

The burning rates of solid rocket propellants are measured by two different methods. The first of these is done by burning the strand burner many times in an nitrogen environment with values determined under constant pressure (P = Constant) as pre-mentioned in the burning rate measurement methods. Measurements conducted with this system are costly and requires much time. In this study, measurements of burning rates were conducted with the method of constant volume and different pressures, which is a new method. In this method, referred to as constant pressure closed bomb, the burning rate measurement of the propellants

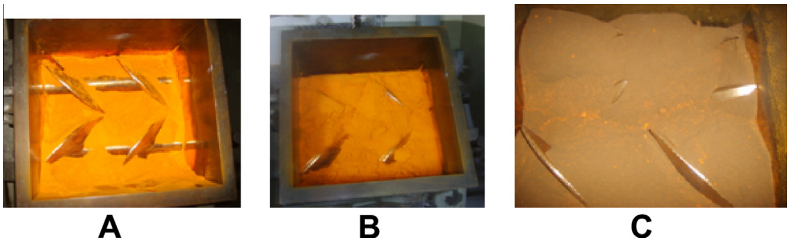

Fig. 14. Here; in A mixing machine DB-1 solid propellant component, In B, DB-2 solid propellant component which was formed by adding 2% Al to DB-1 solid propellant component. In C, DB-3 propellant component that was formed by adding 4% Al to DB-1propellant component are shown.

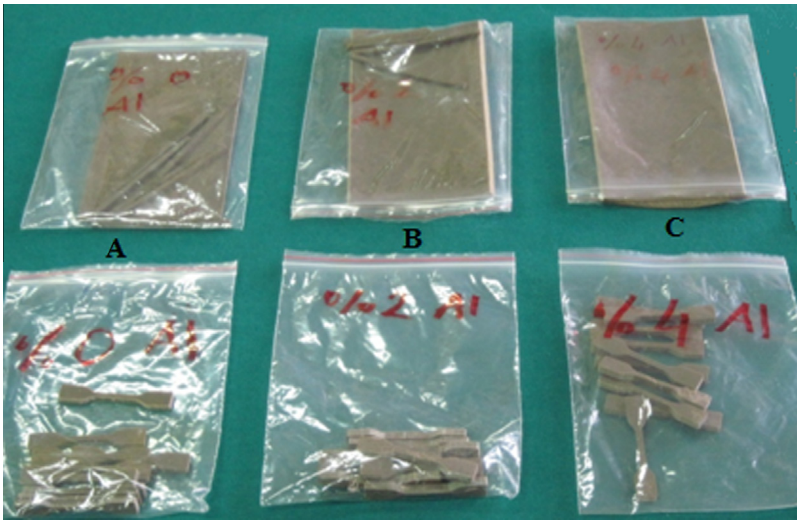

Fig. 15. (A) DB-1 double base propellant with no Al additions, (B) DB-2 propellant into which%2 of Al and (C) DB-3 propellant into which% 4 of Al.

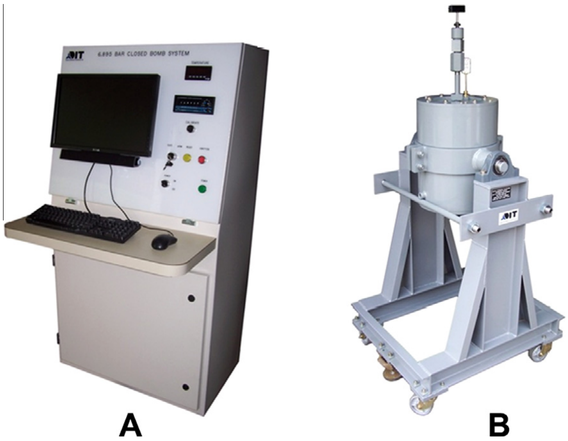

Fig. 16. This system that we used measures solid propellant burning rate with the closed bomb method. (A) control computer unit and (B) closed bomb unit.

Fig. 17. The instrument used in measurement of density of the solid propellant samples with the degree of accuracy as 0.0001.

Table 3
Energy levels of double base (DB) propellant samples produced in three different compositions.

Propellant samples		DB-1	DB-2	DB-3
Combustion heat	Cal/g	813.5698	845.57820	880.4039
	Joule/g	3400.7200	3536.6000	3680.0900

Table 4
Burning rate values of three different double base solid rocket propellants (DB-1, DB-2, DB-3) under pressure increase conditions.

Propellant samples			
Pressure (MPa)	DB-1 burning rate (mm/s)	DB-2 burning rate (mm/s)	DB-3 burning rate (mm/s)
10	10.30	12.60	14.40
20	18.70	19.90	23.30
30	24.30	26.80	32.30
40	30.90	35.00	42.90
50	39.50	42.80	52.80
60	46.20	48.10	60.90
70	53.10	60.00	71.13
80	60.00	65.80	79.60
90	66.40	71.80	83.20

was conducted more economically and in a shorter time, in a single shot under different determined pressures. The burning rates for each propellant samples under different pressures are shown in Fig. 12. In order to ensure the same measurement conditions, the burning rate measurements were taken after the propellant samples were conditioned at 291 K temperature environment for 8 h in the 200 cm^3 volume part referred as closed bomb as shown in Table 4.

When the burning rate results of each of the three propellant samples are considered with respect to the same pressure categories, it was found that as the percentage of A1 volume increases, the burning rates of both DB-1 and DB-2 increase, as seen in Table 4.

The measurement of burning rates of three different propellants referred as double base (DB) was achieved by using a new technological method of high-frequency sound wave changes under different pressures at constant volume conditions as shown in Fig. 18.

The burning rate of DB-2 was found to be higher than that of DB-1 at same measurement conditions. With the addition of A1 into DB-3, the burning rate of this propellant was seen to increase when compared to that of DB-2.

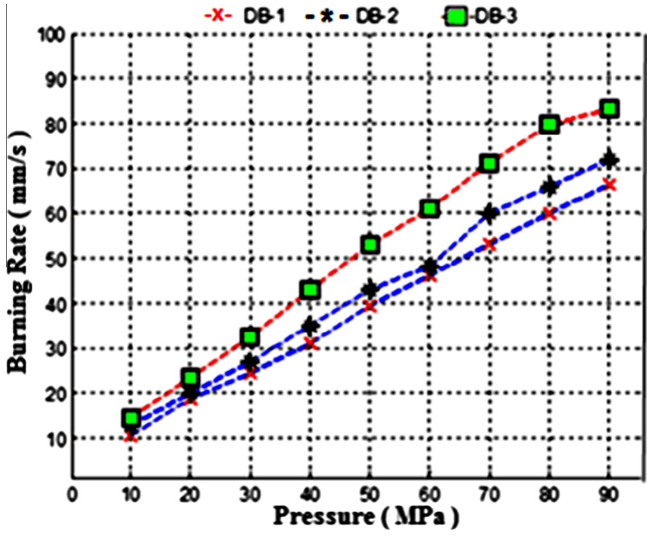

Fig. 18. Burning rate changes of three different double base solid rocket propellants (DB-1, DB-2, DB-3) under different pressure conditions.

Table 5
Percentage (%) of weight of the produced solid rocket propellants.

Solid propellant components	DB-1	DB-2	DB-3
Nitrocellulose (NC)	50.5000	49.4900	48.4800
Nitroglycerine (NG)	36.5000	35.7700	35.0400
Dietilftalat (DEP)	9.0000	8.8200	8.6400
2Nitrodiphenylamine (2NDPA)	2.6000	2.5480	2.4960
Lead salicylate (PbSa)	1.2000	1.1760	1.1520
Candilillawax	0.2000	0.1960	0.1920
Al	0.0000	2.0000	4.0000

Table 6
The density of solid propellant samples.

Propellant samples	Air environment weighing (gram)	Weighing in pure water (gram)	Density (g/cm^3)
DB-1	1	0.368083	1.58
DB-2	1	0.375881	1.60
DB-3	1	0.383677	1.62

The pressure which occurs in the combustion chamber and the gas production rate determines the performance of the rocket motor. The gas production of the solid propellant density in unit of time depends on the burning rate and the surface area. The solid propellant density and the burning rate are among the main factors that directly affect the rocket performance. The experiments show that adding the high energetic metallic Al into double based solid propellant ingredient increases the energy level and the density of the solid propellant that results in. Thus, increase in the density, the energy level and the burning rate will improve the rocket operating performance.

4. Conclusions

Improvement of the burning rate of solid propellants has always been an important research subject. The burning rate of a solid propellant varies depending on many factors. Among these factors, the nucleus structure of the rocket motor directly affects the working performance. The most appropriate nucleus geometry for the rocket motors running with solid fuels is a star-shaped one. The initial temperature (T_0) of solid propellants directly affects the burning combustion chamber pressure and burning rate. As the combustion chamber pressure increases, so does the burning rate. It is seen that as the energy levels of the solid fuels increases, so do their burning rates.

When the burning rate measurement methods of solid propellants are compared, ultrasonic (high-frequency sound wave) method is preferred to the strand burner method, since the former is more economic and practical. In addition, during the rocket motor operation for testing purposes, the burning rate of solid propellants can be measured.

As a result of the measurements in this study, the burning heat of DB-2, which was produced by adding 2% of A1 into the content of DB-1 sample increased by 3.78%. The burning heat of DB-3 which was produced by adding 4% of A1 into the content of normal fuel DB-1 increased by 8.21%. In order to compare the burning rates of the propellants, the sum of the burning rate values each of which was measured separately under determined pressures were taken and the average burning rate of each sample propellant was determined. The average burning rates of DB-1, DB-2, and DB-3 were determined as 38.82 mm/s, 42.53 mm/s, and 51.17 mm/s, respectively. When DB-2 propellant into which 2% of A1 was added, was compared with DB-1 double base propellant with no A1 additions, the average burning rate of DB-2 increased by 9.5%. The average burning rate of DB-3 in which 4% of A1 was added, increased by 31.81% when compared with DB-1. The current experimental study in which A1 was added to the sample propellants showed similar behaviors found by other studies in the literature.

In future work, adding in different properties and different mass of metals like aluminum (Al), boron (B), magnesium (Mg) to the solid propellant components will make important developments in increasing the solid propellant energy density and burning rate. Moreover, since smokeless nitramine based high energetic RDX ($C_3H_6N_6O_6$), HMX ($C_4H_8N_8O_8$) and the metallic supplements have high energy level such as Al, Mg, and Boron, adding these materials to double based ingredients might increase the energy and burn rate.

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