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Experimental Approaches to Develop a High Thrust Ratio in a Single Chamber Dual Thrust Motor Using a Composite Propellant Formulation Based on HTPB/AP/Al

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Abstract: A high thrust ratio in a single chamber dual thrust motor is required to reach a peak velocity very quickly. To achieve a high thrust ratio in a single chamber dual thrust motor, a composite propellant grain, which acts both as booster and sustainer, based on HTPB/AP/Al (84% solid loading) with low aluminum content and having a burning rate of 25±0.5 mm/s at 7 MPa, was successfully developed. This was studied for viscosity build-up, mechanical and ballistic properties, followed by casting and curing as a single type propellant grain. The high burning surface area was created by making grooves of 3 mm width and 60 mm depth over the surface of the nozzle side of the grain while casting and a prototype, thus obtained, was static tested. The data revealed that a grain with one groove demonstrated a thrust ratio of 8, while two grooves, realized a thrust ratio of 30. The experimental thrust ratio values achieved are also in agreement with the predicted values of the thrust ratio of the same composition.

Keywords: dual thrust ratio, single chamber, composite propellant, high burning rate, burning surface area

1 Introduction

Conventional solid composite propellant grains having a 6 star petal configuration based on HTPB/AP/Al exhibit a dual thrust ratio of 1 due to neutral burning [1-3]. The neutral burning can also be achieved by a grain having a geometrical configuration of fin-o-cyl type [4-6], slotted tube type [7], anchor shape [8], *etc*. The neutral burning, based on the above geometrical grain configurations exhibit a slow peak pressure achievement, especially for the lower range of missiles which are unable to change the thrust level upon command.

To overcome this difficulty and to extend the usefulness of rocket motors for tactical applications, the propellant grain and motor hardware were designed in such a way that the desired thrust-time could be achieved in a missile requiring a short duration high thrust level during the initial phase of flight. However, a relatively lower but sustained thrust level is required to overcome air drag and to provide constant velocity up to the target area. Accordingly, when a boost to sustain thrust ratio on the higher side is required, two separate motor chambers have generally been used, despite the weight penalty and complexity of the additional hardware [9].

It is well known that dual thrust motors are most prevalent in rockets which are atmosphere-bound, since they have to deal with air resistance over most of their flight. It is similar in concept to that of multistage rockets, but much simpler to design and build since there is no requirement for detachable stages, having separate components, *etc*. [10].

Generally, during its operation a dual thrust motor accelerates to higher initial speed, however, since air resistance increases quadratically with speed, it slows down rapidly. Hence, a booster and a sustainer are required to achieve thrust variation. To achieve this, a booster is made up of high burning rate propellant for the initial high thrust and velocity, followed by low burning rate propellant of a sustainer to generate the optimum thrust required to maintain the constant velocity, by compensating gravity and drag losses [11]. Because of the different applications of dual thrust motors, a detailed literature search was carried out. It is clear from the literature that to significantly realize dual thrust, different methods have been cited theoretically/practically. These are: dual chambers or a partitioned chamber, a single chamber with varying nozzle diameter, a single chamber equipped with two different types of propellant, *etc*.

1.1 Approaches for achieving a high thrust ratio

There are different approaches for realizing dual thrust by inserting one or two nozzles into a combustion chamber. However, it is quite difficult to achieve a high thrust ratio where a motor operates in the application temperature range *i.e*. –40 °C to +50 °C. Accordingly, a high thrust ratio can be achieved by optimizing the different parameters, such as motor performance, propellant combustion characteristics, grain design and structure of chamber and nozzle, *etc*. [12]. To realize dual thrust, the following equations can be derived from the internal ballistics of motors [13]:

$$F = C_F P_c A_t \tag{1}$$

$$P_c = \left(aC^* \rho_P \frac{A_b}{A_t}\right)^{1/(1-n)} \tag{2}$$

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

$$\frac{F_B}{F_S} = \frac{C_{FB}}{C_{FS}} \frac{A_{tB}}{A_{tS}} \frac{P_{cB}}{P_{cS}} \tag{4}$$

where F is motor thrust, C_F is thrust coefficient, A_t is throat area of nozzle, P_c is chamber pressure, ρ_p, a and n are propellant density, burning rate coefficient and pressure index, respectively; C^* is the characteristic velocity, A_b is the burning surface area of the grain and subsequently B and S represent boost and sustain.

Thus, it is clear from the above equations that F is a function of C_F, A_t, A_b, a, ρ, n and C^*. Since the parameters C_F, ρ and C^* generally do not change too much, a change in thrust can therefore be achieved by changing the value of A_b, a or n.

1.1.1 Dual chamber or partitioned chamber

The name itself implies that it consists of two separate chambers equipped with two independent nozzles, as depicted in Figure 1. It is essential to ignite simultaneously or sequentially, and for such a configuration, the thrust ratio can be expressed by the following equation:

$$\frac{F_B}{F_S} = \frac{C_{FB}}{C_{FS}} \frac{A_{tB}}{A_{tS}} \frac{\left(a_B C_B^* \rho_{PB} \frac{A_{bB}}{A_{tB}}\right)^{1/(1-n_B)}}{\left(a_S C_S^* \rho_{PS} \frac{A_{bS}}{A_{tS}}\right)^{1/(1-n_S)}} \tag{5}$$

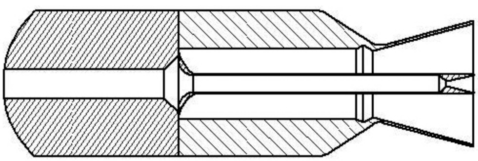


Figure 1. Dual chamber or partitioned motor

Because of the complexity, it is difficult to realize the required thrust ratio from the above equation. Also, the major disadvantage of this technique is that the presence of an additional nozzle increases the inert weight of the motor and thus decreases the overall performance [14]. Efforts were made to counter the inert weight by allowing the first stage to be jettisoned, however, this causes a change in the external shape of the missile resulting in aerodynamic instability and control problems [12].

1.1.2 Single chamber motor with dual propellant

To achieve the desired thrust in a single chamber, the propellant is made up of two types, *i.e.* of high and low burning rates. In this process, the low burning rate propellant with a greater diameter is cast and cured first, followed by the high burning rate composition having a smaller diameter [15-17], equipped with only one type of nozzle as depicted in Figure 2. The thrust ratio equation for such a configuration can be expressed as:

$$\frac{F_B}{F_S} = \frac{C_{FB}}{C_{FS}} \frac{\left(a_B C_B^* \rho_{PB} \frac{A_{bB}}{A_t}\right)^{1/(1-n_B)}}{\left(a_S C_S^* \rho_{PS} \frac{A_{bS}}{A_t}\right)^{1/(1-n_S)}} \tag{6}$$

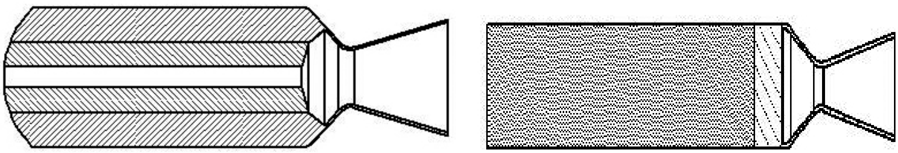


Figure 2. Single chamber motors with dual propellants

It is clear from the above equation that the thrust ratio totally depends upon the burning rate and the available burning surface. However, the main drawbacks of high and low burning rate compositions cast in a single grain are their interfacial bonding and compatibility. Based on Equation 6, other approaches, such as a nozzle with a changeable throat diameter, variations in the burning surface area, *etc*., are also possible to achieve dual thrust in a single chamber motor.

It is clear from the foregoing discussion that there is no information available in the open literature for achieving a dual thrust ratio of up to 30, using a single composite propellant grain based on HTPB/AP/Al, and having a burning rate in the range of 25±0.5 mm/s at 7 MPa using a single nozzle. Consequently, a systematic study has been carried out to achieve a dual thrust ratio of 30 in a single composite propellant formulation by increasing the surface area through grooves on the surface of the grain during casting at the nozzle side and realizing the peak velocity quickly.

In the following section, a high burning rate composition based on

HTPB/AP/Al, introduced into a single chamber dual thrust motor, to achieve a dual thrust ratio of 30 by increasing the burning surface area at the nozzle end through grooves using a single nozzle, is discussed.

2 Experimental

2.1 Materials

Ammonium perchlorate having an average particle size of 200±10 μm was obtained from M/s. Pandian Chemicals, Ltd. (Cuddalore, India). HTPB with a number average molecular weight of 2500 g/mol and a hydroxyl value of 43 mg KOH/g, was received from M/s. Anabond, Ltd., and used as received. Aluminum powder having an average particle size of 15±3 μm, was obtained from M/s. Metal powder company, Madurai, and used as such. Dioctyl adipate (DOA) and toluene diisocyanate (TDI) were procured from Indo-Nippon (Mumbai, India) and BASF (United States), respectively. The solid ballistic modifier, *i.e.*, copper chromite ($Cu_2Cr_2O_5$), with an average particle size of 2 μm, was received from trade and used after heating at 105 °C for 4 h.

2.2 Characterization

The particle size of the solid raw materials used in the present study was determined using a CILAS particle size analyzer, Model 1064L, France, based on the laser technique. The instruments work on the diffraction of monochromic light on the surface of the particles with the angle of diffraction depending on the particle size. Generally, the higher the diffraction angle the lower the particle size and *vice versa*.

A Brookfield dial type viscometer, Model HBT, was used for the measurement of the end of mix (EOM) viscosity and viscosity build-up of the propellant slurry by inserting a T-C spindle at a rotation speed of 2.5 rpm at a predetermined temperature. Density determinations were carried out using a gas pycnometer, Thermo-fisher, USA, using helium gas as the medium at 30 °C.

The mechanical properties, such as tensile strength, elastic modulus (initial slope of the stress-strain curve) and percentage elongation, were determined on a Hounsfield universal testing machine (UTM) using dumbbells conforming to ASTM D-638 Type-IV, at a cross head speed of 50 mm/min at ambient temperature.

The shore hardness A of the developed cured composition was determined by a digital shore durometer, Model No. 6307, Germany, conforming to ASTM 02240 and ISO 868, by pushing 2.5 mm of the protruded probe onto the surface of the cured propellant at ambient temperature.

The burning rate of the cured propellant samples was determined by the acoustic emission technique in an inert environment (nitrogen) at different pressures using a 750 cm^3 stainless steel bomb [18]. The bomb was equipped with a piezoelectric transducer and a lid with a panel for holding the propellant strands. The acoustic signal was generated by the rapid release accompanying the propellant combustion. The propellant samples were cut into the form of strands having dimensions of 150 mm × 6 mm × 6 mm and ignited from one end using nichrome wire. When the propellant strands burned, an acoustic pulse was generated and measured using an oscilloscope. The burning rate of the propellant strand was calculated by dividing the length of the strand with the duration of the acoustic pulse. An error in the measured burning rate, in the range of ±2%, may be due to dimensional variation of the propellant strand and length measurement.

Vacuum stability tests were performed in triplicate using a vacuum stabilizer, model No. Stabil-21, OZM, Czech Republic, by taking 5 g of samples, already dried at 65 °C for 2 h, in a glass test tube. The vacuum was created by applying suction inside the test tube. The whole system was equipped with a pressure transducer and heated at 100 °C for 40 h. The gaseous volume was measured after attaining room temperature. The results of the gaseous volume obtained per gram are reported as an average of three test samples [19].

The ageing study of the developed composition was evaluated by using a micro calorimeter, thermal activity monitor model No. TAM-III, TA instrument, USA, at 90 °C for 84 h, as per STANAG 4582.

2.3 Procedure

A vertical planetary mixer was employed for mixing the propellant formulations. The general procedure followed was as follows.

Initially, all of the binder ingredients (HTPB, DOA and bonding agent) except the curing agent were weighed as per the composition and added to the mixer bowl. The mixture was mixed as per a predetermined cycle, followed by evacuation under vacuum. After this, the solid burning rate modifier was added and mixed, followed by the aluminum powder with mixing for a further 30 min. After complete mixing of the Al powder in the binder matrix, ammonium perchlorate of two different sizes (coarse and ultra fine) were added one after another and mixed at 40±2 °C. Subsequently, TDI was added as the curing agent and mixed for a further 30 min. A sample was removed from the completely mixed propellant slurry for viscosity measurement. The propellant slurry was then cast into a control mould under vacuum. The cast propellant slurry was subjected to curing at elevated temperature (50 °C) in a water-jacketed oven. Samples were prepared from the cured propellant for evaluation of the mechanical, thermal and ballistic properties, as well as grooved grains for static testing.

3 Results and Discussion

Initially, two theoretical approaches are discussed for achieving a dual thrust of 30, which were worked out by considering two grain configurations with different burning surface areas in a single grain. Accordingly, a high burning rate composition based on HTPB/AP/Al was chosen, having a burning rate of 25±0.5 mm/s at 7 MPa, to realize a dual thrust ratio of 30 in a single chamber dual thrust motor. The developed composition was studied for its viscosity build up, mechanical, thermal and ballistic properties before casting into the main grain configuration. The details of the developed composition used in the present study are presented in Table 1, along with those of the reference composition. The developed composition was chosen in preference to the reference composition mainly due to its low viscosity and ease of processing in a smaller web grain.

Table 1. Formulation details of high burning composite propellants

Sr. No.	Ingredient	Ingredient [%]	
		Developed composition	Reference composition
1	Binder (HTPB +DOA+TDI)	15	20
2	AP coarse (200 μm)	20	7.5
3	AP fine (6 μm)	59	69
4	Al powder (15 μm)	5	2.5
5	Ballistic modifier (copper chromite)	1	1

3.1 Approaches for realizing a high thrust ratio in a single chamber dual thrust motor using one type propellant

It is well known that by considering a single propellant and a single chamber equipped with a single nozzle, the boost-sustain duration responsible for negligible influence of C_F, the thrust ratio Equation 6 at such a condition, can be simplified as:

$$\frac{F_B}{F_S} = \left(\frac{A_{bB}}{A_{bS}}\right)^{1/(1-n)} \tag{7}$$

The above equation clearly envisages that by changing A_b using a single nozzle, it is more likely to realize a high thrust ratio. In practice, for achieving dual thrust, the preferred approach is to use a single nozzle without changing the throat diameter due to its simplicity and reliability. In the present study, the designed pressure ratio depends upon the thrust ratio, therefore the required burning surface area can be easily achieved by grain design parameters. Based on this, two types of grain configuration were selected to realize a high thrust ratio of 30.

3.2 Grain configuration with a single groove

In the single groove grain, the grain was designed to have a groove width of 3 mm and a depth of 60 mm having a distance of 25 mm from the centre of the grain at the nozzle end as depicted in Figure 3, bearing in mind the high burning rate propellant of 25±0.5 mm/s at 7 MPa and with a pressure exponent of 0.4. However, the selected dimensions of the groove at the nozzle end generates a ratio of the initial burning surface area (boost) to the cylindrical solid burning surface (sustain) of around 3.5 which can provide a maximum thrust ratio of only 8.

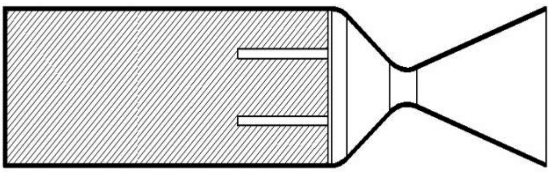


Figure 3. Single chamber motor with one type of propellant having a single groove

3.2.1 Grain configuration with two grooves

To realize an expected thrust ratio of 30, grain is designed with two grooves having the distances 11.75 mm and 38.25 mm from the centre of the grain respectively at the nozzle end with a width of 3 mm and a depth of 60 mm as depicted in Figure 4. In this approach, the ratio of the initial burning surface area (boost) to the cylindrical solid burning surface area (sustain) would be around 7.7 which meets the expected thrust ratio of 30 using the high burning rate composition of 25±0.5 mm/s at 7 MPa with a pressure exponent of 0.4.

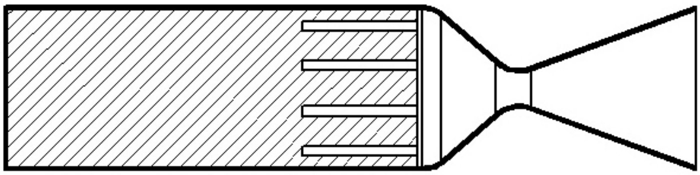


Figure 4. Single chamber motor with one type of propellant having double grooves

Based on the two approaches, a detailed study of the high burning rate propellant composition with its better processability, mechanical and ballistic properties was carried out, before casting into the proposed two configurations to realize a high thrust ratio of 30.

Table 2. Data on viscosity build up, mechanical and ballistic properties

Sr. No.	Property	Developed composition	Reference composition
1	EOM viscosity, 40 °C [Pa·s]	992	1344
2	Viscosity after 1 h, 40 °C [Pa·s]	1040	1440
3	Viscosity after 2 h, 40 °C [Pa·s]	1088	1568
4	Viscosity after 3 h, 40 °C [Pa·s]	1152	1760
5	Mechanical properties		
	a. Tensile strength [MPa]	0.75	1.2
	b. Elastic modulus [MPa]	4.1	6.5
	c. Elongation [%]	43	25
6	Hardness shore A	65	75
7	Ballistic properties		
	a. Burning rate at 7 MPa [mm/s]	25±0.5	25±0.5
	b. Pressure exponent	0.4	0.4
8	Vacuum stability at 100 °C, 40 h/cm^3/g	0.12	0.12
9	Ageing/Shelf life [years]	>10	>10

3.3 Viscosity build up of the developed composition

A composition developed from the reference composition by reducing the content of fine AP was studied for its viscosity build up using a Brookfield viscometer by inserting the T-C spindle at 2.5 rpm and 40 °C, and the data obtained are presented in Table 2. These data clearly revealed that the end of mix viscosity (EOM) of the developed propellant slurry was 992 Pa·s at 40 °C while the reference composition exhibited EOM of 1344 Pa·s at the same temperature.

Furthermore, the viscosity build up data for 3 h clearly demonstrated that the buildup is not very fast and could rise to 1152 Pa·s at 40 °C (1760 Pa·s for reference composition), which is very much castable by the gravitation casting technique. In view of the low viscosity and build up compared to the reference composition, and its ease of processing, the developed composition was used in a single chamber dual thrust motor to realize a thrust ratio of 30.

3.4 Evaluation of the mechanical properties

The evaluation of the mechanical properties, such as tensile strength (TS), elastic modulus (E-mod) and percentage elongation of the cured propellant sample, was carried on a Hounsefield universal testing machine (UTM) and the results obtained are presented in Table 2. These data revealed that the tensile strength of the developed composition was 0.75 MPa, whereas the TS of the reference composition was 1.2 MPa. In the same way, the elastic modulus of the developed composition was 4.1 MPa compared to 6.5 MPa for the reference composition. The percentage elongation of the developed composition was on the high side compared to the reference composition. The lower TS and E-mod of the developed composition may be due to the presence of a smaller quantity of fine AP compared to the reference composition.

The results of the shore hardness A of the developed cured composition are presented in Table 2. It is clear from the table that the shore hardness of the developed composition was 65 whereas the shore hardness of the reference composition was 70 due to the higher percentage of fine AP incorporated in the composition.

The density of the cured propellant was determined by gas pycnometry using helium gas as the medium at 30 °C, and the data obtained are presented in Table 2. These data clearly revealed that the densities of the developed and reference compositions were 1630 kg/m^3 and 1625 kg/m^3, respectively. The marginally higher density in the case of the developed composition may be due to the higher percentage of aluminum powder in the composition.

3.5 Evaluation of the ballistic properties

3.5.1 Burning rate

Solid strand burning rate (SSBR) samples (150 mm × 6 mm × 6 mm) were prepared for the developed cured composition along with the reference composition. The burning rates were determined by the acoustic emission technique in the presence of an inert atmosphere at 7 MPa and the data obtained are presented in Table 3. It is clear from these data that both compositions demonstrated almost the same burning rate, *i.e.* 25±0.5 mm/s at 7 MPa. The burning rate data of the developed composition are reproducible, and hence it was selected for the high thrust ratio in a single chamber dual thrust motor.

Table 3. Data on the performance of grain configurations having a single groove and two grooves in a single chamber dual thrust motor

Sr. No.	Parameter	Grain configuration of a single groove	Grain configuration of two grooves
1	Weight of propellant grain [kg]	2.2	2.1
2	Ratio of burning surface area	3.5	7.7
3	Thrust ratio based on prediction	8.0	30.0
4	Boost phase pressure [MPa]	8.1	16.7
5	Sustainer phase pressure [MPa]	1.02	0.56
6	Boost phase thrust [MPa]	34.07	68.28
7	Sustain phase thrust [MPa]	4.25	2.29
8	Thrust ratio achieved	8.01	29.82

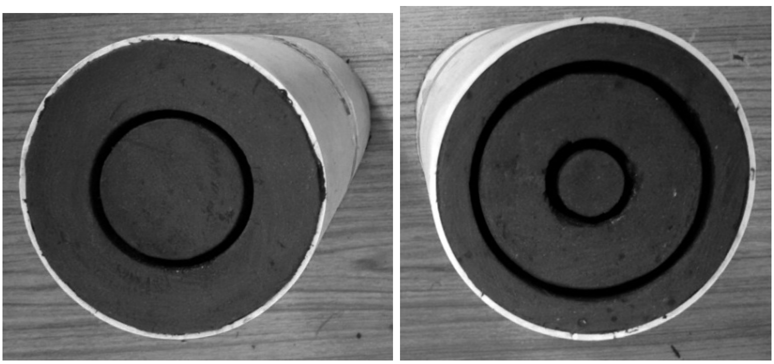
3.5.2 Pressure exponent (n)
The pressure exponent (n) was determined using the SSBR data at different pressures by plotting a curve of $\log_e$ (burning rate) *vs*. $\log_e$ (pressure) and calculating n from the slope of the curve [20]. The data obtained are presented in Table 2. It is clear from these data that the pressure exponent of the reference composition as well as that of the developed composition was 0.40. This n value for a very high burning rate composition is also quite satisfactory and safe for further study in a single chamber dual thrust motor.

3.6 Vacuum stability and ageing/shelf life
The vacuum stability (VS) of the cured propellant samples was performed in a vacuum stabilizer, by treating a 5 g sample at 100 °C for 40 h, and the results obtained are presented in Table 2. It is clear from the results that the developed composition is safe and comparable to the reference composition, as the VS values per gram of the samples were 0.12 cm^3. The standard values of VS at the same temperature and conditions should not exceed 2.0 cm^3 per gram of sample.

The ageing study of the developed composition was also evaluated using a micro calorimeter, TAM-III, by taking 5 g of sample in an ampoule made of haste alloy at 90 °C for 84 h in a Mobil-Therm oil bath and the data obtained are presented in Table 2. It is clear from these data that the shelf life of the developed composition was more than 10 years, as the heat developed was 30 µW instead of the standard 350 µW for 10 years.

3.7 Ballistic evaluation motor based on the single groove grain configuration

The finalized composition based on HTPB/AP/Al, having a burning rate 25±0.5 mm at 7 MPa and with a pressure exponent value of 0.4, was cast and cured using the first grain configuration having a single groove. The outer diameter of the grain was 110 mm while the length was 200 mm. The total weight of propellant was 2.2 kg. The cured grain having a single groove is shown in Figure 5a. The fully cured grain was conditioned at 27 °C for 24 h before assembling in a ballistic evaluation motor equipped with a single nozzle with a throat diameter of 17 mm for configuration one, and static tested. The pressure-time curve as well as the thrust-time profiles are presented in Figure 6, and the data obtained are listed in Table 3. It is clear from both the figure and table that the grain configuration using a single groove realized a boost-sustain ratio of only 8. The table further revealed that in configuration one, the boost phase pressure was 8.1 MPa while the sustain phase pressure was 1.02 MPa. Similarly, the boost phase thrust was 34.01 MPa while the sustain phase thrust was about 4.25 MPa, clearly confirming that the thrust ratio was 8.01, very close to the predicted value of 8.



a. b.

Figure 5. Configuration of propellant grains having (a) a single groove, and (b) two grooves

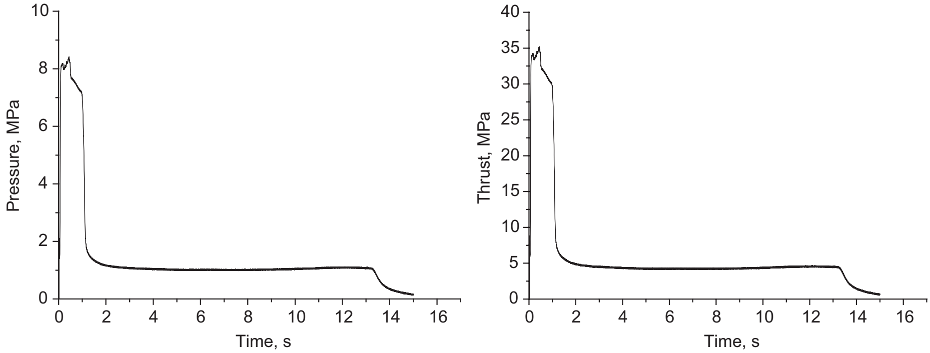


Figure 6. Pressure-time and thrust-time profiles of the single groove configuration

3.8 Ballistic evaluation motor based on the two grooves grain configuration

It is clear from the earlier study that a single groove grain configuration on a static test resulted in the thrust ratio of 8.01, therefore a two grooves grain configuration using the same dimension and weight of cured propellant was used for a static test. The cured grain having two grooves configuration is shown in Figure 5b. Furthermore, as with the single groove grain configuration, the grain was conditioned at 27 °C for 24 h before the static test equipped with a single nozzle having a throat diameter of 19 mm. The pressure-time and thrust-profiles obtained after static testing are presented in Figure 7 and the data obtained are listed in Table 3. It is clear from both the figure and table that using the two grooves configuration, the boost-sustain ratio was 29.82. Thus, it is clear from the table that with a two grooves configuration, the boost phase pressure was 16.7 MPa while the sustain phase pressure was about 0.56 MPa. Similarly, the boost phase thrust was found to be 68.28 MPa while the sustain phase thrust was 2.29 MPa, clearly confirming that the thrust ratio was 29.82, which is very close to the predicted value of 30.

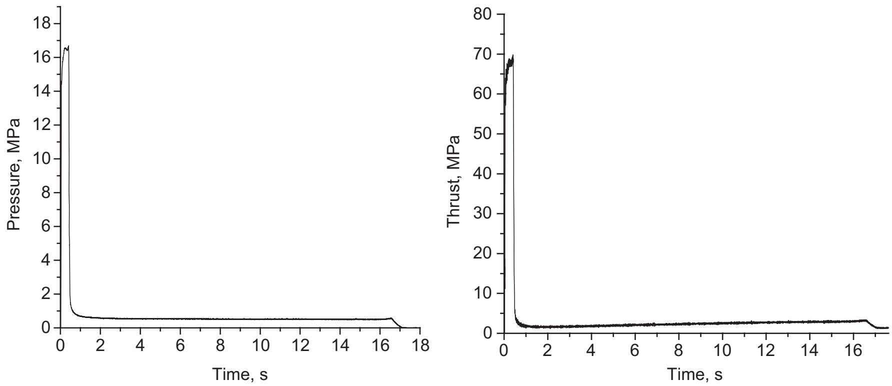


Figure 7. Pressure-time and thrust-time profiles of the two grooves configuration

Based on the above findings, it is clear that further enhancement in the thrust ratio is possible using a single chamber and a single propellant composition by increasing the surface area with the help of carving out another groove at the nozzle end. However, on adding second groove, the flow path for the propellant slurry becomes narrow, which causes difficulty in casting. However, the above problem may be alleviated by using a larger diameter grain, but a larger diameter would increase the burning surface area of the sustainer, and thus further improvement in the thrust ratio is practically unfeasible.

4 Conclusions

A successful attempt has been made to incorporate a high burning rate propellant composition based on HTPB/AP/Al, having a burning rate 25±0.5 mm/s at 7 MPa with a pressure exponent of 0.4, in a single chamber dual thrust motor. The developed composition was static tested in a grain configuration of a single chamber dual thrust motor having a single or two grooves of 3 mm width and a depth of 60 mm. The data revealed that with a single groove the thrust ratio was 8.01, while using a two grooves grain configuration, a thrust ratio of 29.82 was realized, successfully meeting the predicted values of 8.0 and 30.0, respectively, for a single chamber dual thrust motor. The developed grain configuration having two grooves may find application where high peak pressure is preferred, especially in tactical missiles.

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