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Propulsion theoretical and experimental analysis of composite propellants motors

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Propulsion theoretical and experimental analysis of composite propellants motors

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Abstract. Rockets have revolutionized space technology and human space exploration. Most rockets and missiles are both propelled by rocket motors that use composite solid propellants. The ICT code and the NSAS CEA code are two programs that can be used to forecast theoretical propulsion parameters for composite solid rocket propellant. Rocket propellant performance is governed by a specific impulse factor, which is calculated theoretical and experiment. In this paper, the theoretical specific impulse for different composite solid propellant formulations at 70 bar combustion pressure and an adapted nozzle (optimum expansion) were calculated by the NASA-CEA code and the ICT code. Meanwhile, a static firing test was performed on a small scale test motor to experimentally determine the actual specific impulse. The objective is to verify theoretical calculations from two codes with experimental data, via the determination of the specific impulse deviation co-efficient.
Keywords: Composite solid propellant, NASA CEA, ICT Code, and Specific impulse.

1. Introduction

Rockets played a significant role in advancing space travel technology and increasing humanity's understanding of the cosmos. Composite propellants combine fuel and oxidizer in a motor and are then ignited to propel rockets and missiles. A rocket propellant's effectiveness is measured by its specific impulse, or the ratio of thrust to mass flow rate. Composite solid propellants find widespread use in today's rockets and missiles. Future time, composite solid propulsion presumably will reduce costs, increase performance, enhance dependability, and have a smaller ecological footprint. With that in mind, it's time for a new wave of solid propellants, with cutting-edge oxidizers and binders. Components of composite propellants include oxygen-donating inorganic salts and a plastic binder. The polymeric matrix of the mixture contains a solid oxidizer, metal powder that serves as a secondary fuel component, cross-linking and curing agents, plasticizers, and other additives. Almost all composite propellants employ aluminum as a fuel. It is suitable to high solid loading and comes in the shape of tiny spherical particles. Aluminum is safe to handle because it has an aluminum oxide layer that prevents the metal's grains from reacting to moisture [1-3].

Binder and other fuels need oxygen, which can be provided by a good oxidizer, in order to create the highest heat of combustion and enthalpy of formation. In the beginning, composite propellants employed potassium perchlorate as their oxidizer. It's not extremely energising, but it's sturdy, compatible, and insensitive. The more powerful and generally safe to handle oxidizer in composite propellants, ammonium perchlorate (AP), swiftly took its place. Because to the high oxidant content of AP, its self-deflagration may be maintained at pressures more than 20 bar. Because fine AP burns quicker than coarse AP in propellants, the particle size distribution of AP has a considerable impact on burning rate tailoring [4-5].

Binders are enclosing compounds that keep a charge of finely separated particles together and increase the propellant grain's mechanical strength. HTPB, CTPB, resins, plastics, and asphaltics are all examples of prepolymers with functional ends. A positive enthalpy of formation (H,) and a binder structure that burns to produce gases with a low molecular weight are also necessary conditions. High mechanical properties and strong adhesion between the solids loading are required of the binder in propellant compositions. The superior mechanical characteristics and very good adhesion with Aluminum and Ammonium Perchlorate led to the development of hydroxyl terminated polybutadiene as the standard binder for composite propellants [6-7].

Software like that created by the Fraunhofer Institute for Chemical Technology (ICT) or NASA's Chemical Equilibrium with Applications (CEA) may mimic a rocket motor's performance with a specific composite propellant, allowing researchers and engineers to test different configurations and designs. Theoretical specific impulse of a composite propellant at various conditions, including combustion pressure and nozzle expansion ratio, can be calculated using these codes. Initiating a combination of AP/HTPB/Al as the primary composite propellant is the primary focus of this endeavor. The theoretical rocket performance of the resulting mixture is calculated, and its chemical equilibrium composition and qualities are ascertained with the help of the other program. Parametric analysis is carried out using software forecasts, while the energetic oxidizers and fuels are changed in order, and theoretical rocket performance characteristics are recorded, such as Specific Impulse and Characteristic Velocity [8-9].

In addition to theoretical calculations, static firing tests on a miniature test motor used to evaluate a composite propellant's actual specific impulse. In these experiments, the motors are ignited, the thrust and mass flow rate are recorded, and Isp is derived from these parameters.

2. Thermochemical calculation

Theoretical composite propellant motors performance can be calculated by two different computer programmes: the NASA-CEA (NASA Lewis Research Center) code and the ICT (Fraunhofer Institute for Chemical Technology) code. The NASA-CEA code is a software tool developed by the National Aeronautics and Space Administration that can predict the performance of rocket propellants based on chemical equilibrium calculations. It takes into account the propellant's characteristics, the combustion chamber conditions, and the nozzle geometry to calculate the specific impulse, thrust, and other performance parameters.

The ICT code, on the other hand, is a program developed by Fraunhofer Institute for Chemical Technology in Germany. To forecast the efficiency of composite propellants, it takes a new tack, one that is grounded in empirical correlations and statistical research. As such, it finds extensive application in the aerospace sector, where it is utilised for designing and optimising rocket motors.

The input data for the two programs are combustion pressure (Pc), exist pressure (Pe), the weight percentage, density, enthalpy of formation, and summary formula of each component of the propellant formulation. The output results from two codes are Isp, density, exhaust velocity, combustion temperature. In this study, ICT code and NASA CEA code were employed for the calculations of about 12 composite propellant formulations. (AP), (Al), and (HTPB) were studied as composite propellant components. The combustion pressure was set to 70 bar, and the ratio of nozzle expansion was adapted to optimize the motors' performance. The ratios of AP, Al, and HTPB were varied from AP/Al/HTPB (74/12/14) to (62/24/14) while keeping the binder ratio constant and increasing the aluminium metal powder ratio at the cost of the AP ratio by step one. Specific impulse and other performance parameters of the motors were calculated theoretically using the NASA-CEA code and the ICT code.

3. Experimental

3.1. Material

Ammonium perchlorate (AP) was employed in three different particle sizes: 400, 200, and 7-11 microns (μ). (Abo Zaabal factory, Egypt). Aluminum (Al) particles between 40 and 20 micrometres (μ) in size (Aldrich Chemical Co., England). Pre-polymer hydroxyl-terminated polybutadiene (HTPB) from Iverise Co., Brazil has a density of 0.9 g/cm3 and an OH value of 0.8% (Mn=2500-2900 on average). Usage of dioctylazelate (DOZ) as a plasticizer (Aldrich Chemical Co., UK) (Aldrich Chemical Co., England). Hexamethylene diisocyanate (HMDI)-curable (Aldrich Chemical Co., England).

3.2. Preparations of 6 inch small test motor

The composite propellant was prepared using a casting procedure in a vertical kneader. The pre-polymer and plasticizer were mixed at 50-60 °C, followed by the addition of aluminum metal powder and mixing for 15 minutes. The oxidizer was then added in three stages, and mixing was continued for 15 minutes after each stage. The ratio of NCO to OH is 0.7. Curing agent HMDI was added to the mixture. Figure 1 shows the cured propellant within a 6-inch tiny test motor after 7-10 days in an electric oven at 55 °C. The main constituents of the composite solid propellant were 69% ammonium perchlorate, 17% aluminum metal powder, and 14% polyurethane matrix in weight percentage, as listed in Table 1.

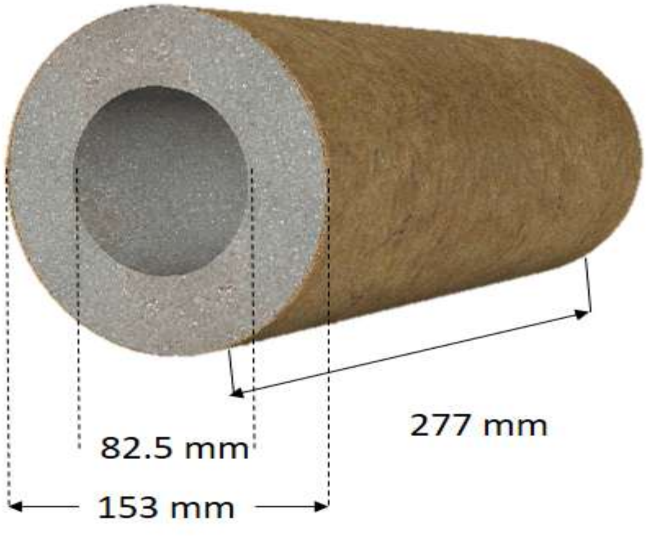

Figure 1. 6-inch test motor grain dimension

Table 1. Formulations of composite propellants and their components weight percentage.

Function	Ingredients		Average size	Percentage
Oxidizer 69%	AP (NH_4ClO_4)		400 micron	40%
	Ammonium perchlorate		200 micron	15%
	(tri-model)		7-11 micron	14%
Metal fuel 17%	Al		22-40 micron	10%
	(bi-model)		10-20 micron	7%
Fuel binder 14%	per polymer	HTPB		10%
	Cross linking agent	HMDI		0.63%
	Bonding agent	MT-4		0.3%
	plasticizer	DOZ		2.4%
	antioxidant	Cyanox		0.14%
	Burning rate modifier	Cupper chromate		0.03%

3.3. *Measurement of ballistic performance parameters*

Standard testing rocket motor (6 inch motor) furnished with modified nozzle expansion ratio at test rig was used to measure performance characteristics such as burning rate, operating pressure, specific impulse, and characteristic exhaust velocity of the prepared propellant formulations. The rocket motor's thrust is measured via a load cell. A pre-load screw fastened to a strong concrete block that counteracts the force exerted by the motor forms the final piece of the load cell's seamless construction. The bench's cell axis must be in perfect alignment with the rocket motor's thrust axis, so keep that in mind while you construct it.

The pressure transducer information includes: Model AOV/MOV, full bridge strain gauge type, pressure range of 200 bar, full scale accuracy of 0.5%, robust integrated connector, frequency greater than 100 kHz, and output pressure of 2mv/v. The following are the technical details of the thrust transducer that is being utilized for the measurement: Model HBM C2 full-bridge strain gauge load cells with a 10kN thrust upper limit, a 10kN accuracy tolerance, and a frequency response of 19.3kHz.

4. Results and discussion

4.1. *Theoretical calculations*

The rocket performance parameters for the various constituent percentages available in the propellant. The propellant combinations from AP/Al/HTPB (74/12/14) to (62/24/14) are tested at chamber pressures 70 bar. It is assumed here the supersonic area ratio is adapted.

The mixture that works best is found by varying the percentage of Al from 12 to 24 percent of the total mass, with each increase of 1 percent. ICT Code output is seen in Figure 2. A non-monotonic trend is seen that peaks at 20 % of Al by mass. The comparable Isp is roughly 264.6 s. The results from NASA CEA Code are shown in Figure 2 show that peaks at 20 % of Al by mass. The matching Isp is around 263.5 s. Because of this, we can conclude that there exists a sweet spot in the specific impulse that, when reached, yields the highest possible performance from the motors regardless of the composite solid propellant used. To verify these findings and comprehend the processes that govern motor performance across compositional changes, more research is required.

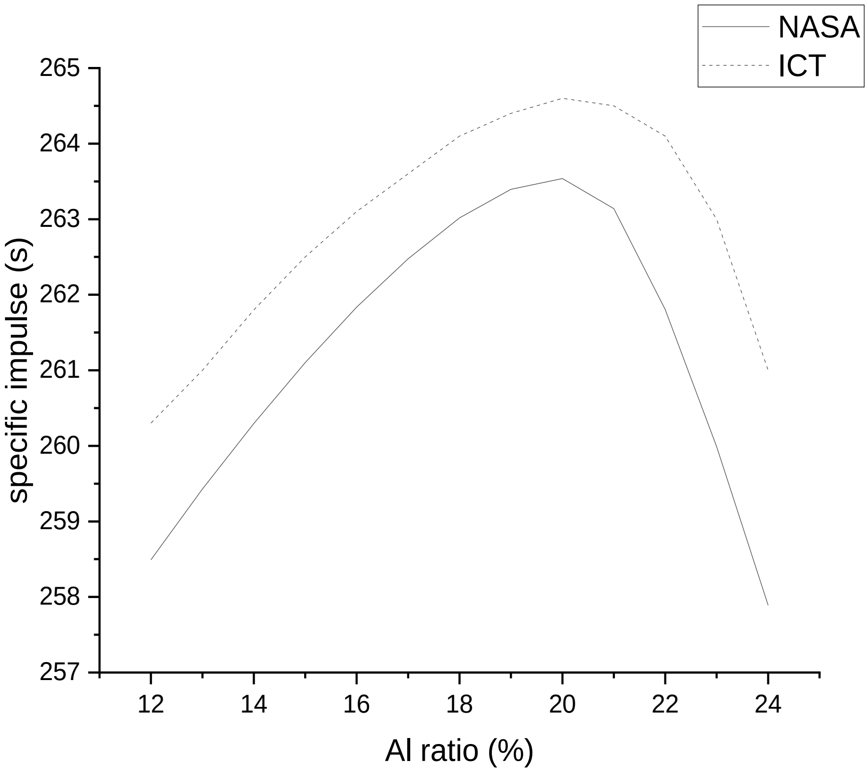

Figure 2. Variation of Isp with Aluminum concentration from NASA and ICT.

4.2. *Experimentally measured ballistic performance parameters*

For the purpose of this research, a composite propellant formulation was chosen to be examined; it contains 69% ammonium perchlorate (AP), 17% aluminium metal powder, and 14% hydroxyl-terminated polybutadiene (HTPB) binder.The propellant was prepared using a particle and casting technique and was used to manufacture three 6-inch test motor. The optimum nozzle expansion ratio is 10.2. The motors were ignited in a test rig and the performance parameters were measured experimentally.

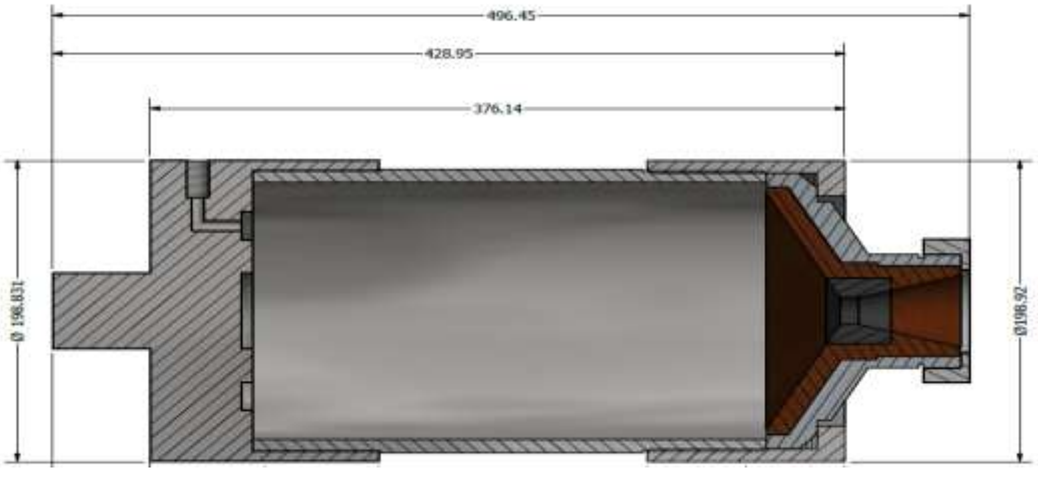

Figure 3. Small scale test motor used in experiment

Figure 4. Firing test for 1-6 inch motor

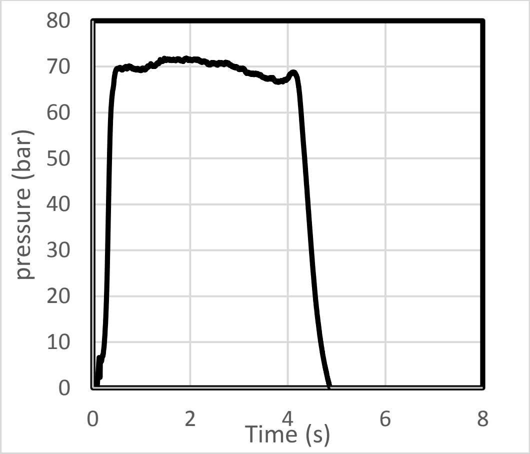

Figure 5. Pressure vs. time curve for 1-6-inch motor

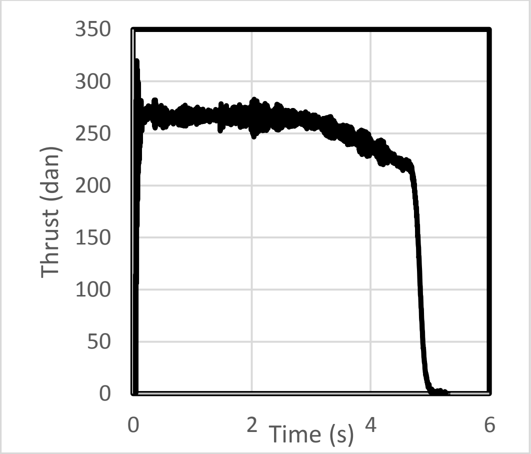

Figure 6. Thrust vs. time curve for a 1-6-inch motor

Table 2 displays the collected experimental data.

Table 2. The experimentally measured ballistic characteristics of selected propellant formulations from three 6-inch motor

Motor type	Experimental results								
	ρ (g/cm^3)	Throat (mm)	Mass (kg)	T (s)	R (mm/sec)	P (bar)	C* (m/sec)	F av. (dan)	I$_{sp}$ (sec)
1-6 inch	1.745	18.1	6.080	4.856	7.32	71.99	1456	287.8	234.7
2-6 inch	1.745	18.1	6.050	5.046	7.27	71.96	1482	274.8	234.1
3-6 inch	1.745	18.1	6.080	5.102	7.07	70.87	1475	274.5	235.2

Where: ρ density of propellant(g/cm^3), C* characteristic velocity (m/s), P average pressure (bar), R burning rate (mm/s), T burning time (s), F av. Average thrust (dan), and I$_{sp}$ Specific Impulse (s).

4.3. The deviation co-efficient result

The specific impulse average mean is 234.67 (s), standard deviation is 0.55, and standard error is 0.3. the final result should then be reported as: Average specific impulse = 234.67±0.3 (s).

Table 3 presents specific impulse and density for a composite solid rocket propellant formulation consisting of 69% ammonium perchlorate (AP), 17% aluminum metal powder, and 14% hydroxyl-terminated polybutadiene (HTPB) binder, as calculated by the ICT code, the NASA-CEA code, and measured experimentally. The deviation coefficient, calculated as the ratio of the measured Isp to the theoretical Isp. This deviation coefficient can be used to quantify the accuracy of the theoretical predictions and to identify any discrepancies between the theoretical and experimental results.

$$\eta = \left| \frac{\mathrm{Isp\ (measured)} - \mathrm{Isp(theoretical)}}{\mathrm{Isp(theoretical)}} \right| * 100$$

Table 3. A Comparison of Density and Specific Impulse

	Density (g/cm^3)	Specific impulse (s)
ICT Code	1.76	263.6
NASA CEA Code	1.752	262.5
6 inch motor	1.745	234.67±0.3
η		10.5%-11%

The results of the theoretical and experimental analyses of the composite propellant motors showed that Isp values estimated using the NASA-CEA code and the ICT code were in good agreement with each other, with a deviation of only 0.4%. However, both codes indicated a bigger deviation from the experimental specific impulse values, with a deviation of (10.5-11) %. This indicates that while the theoretical calculations using the NASA-CEA code and the ICT code are generally accurate, there may be some discrepancies between the theoretical predictions and the actual performance of the composite propellant motors.

5. Conclusion

The specific impulse values estimated with the NASA-CEA code and the ICT code demonstrated good agreement with each other, with a difference of only 0.4%, according to the findings of these calculations. Furthermore, the two codes displayed a bigger discrepancy (10%) from the experimentally determined impulse values. This indicates that while the theoretical calculations using the NASA-CEA code and the ICT code are generally accurate, there may be some discrepancies between the theoretical predictions and the actual performance of the composite propellant motors. Further analysis is needed to understand the sources of these deviations and to identify potential improvements to the theoretical models or the experimental setup.

Overall, this study provides valuable insights into the performance of composite solid propellant motors and the accuracy of the NASA-CEA code and the ICT code for the prediction of specific impulse and other performance parameters to save time, money, and effort form experiments. It also highlights the importance of experimental testing in verifying the accuracy of theoretical predictions and in identifying potential improvements to the effectiveness of rocket propulsion systems.

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