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# Design, Fabrication and Testing of a Hybrid Rocket Engine Prototype

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**ABSTRACT**

Rockets are used for various purposes such as defence applications and the launch and maintenance of satellites in orbit. Among the different propulsion systems used in rockets, chemical fuel rockets are categorized into three groups as solid fuel rockets, liquid fuel rockets and hybrid fuel rockets. Liquid fuel rockets have high cost and complexity whereas solid fuel rockets have the explosion hazard and thrust control problems. Studies on the use of hybrid rockets have increased recently as they offer a safety advantage. In this study, a dedicated test setup was designed and constructed for testing a prototype hybrid rocket engine. Change in thrust with respect to time was measured for the selected PVC/Oxygen fuel/oxidizer. Two different shapes for the inner surface of the hollow, cylindrical fuel were compared: straight and square groove. At the end of the conducted experiments, it was determined that using square groove in the fuel cavity provided 48.6 % improvement in maximum thrust, 52 % in total impulse, 64.8 % in specific impulse and 64.8 % in effective exhaust velocity compared to the straight fuel geometry.

**Keywords:** Hybrid rocket; Thrust; PVC fuel; Rocket engine testing

## NOMENCLATURE

$A_o$ : Outlet area ($m^2$)
$c$ : Characteristic velocity (m/s)
$F_{avg}$ : Average thrust (N)
$F_t$ : Maximum thrust (N)
$g$ : Gravitational acceleration ($m/s^2$)
GOX : Gaseous oxygen
HTPB : Hydroxyl-terminated polybutadiene
$I$ : Total impulse (s)
$I_s$ : Specific impulse (s)
$\dot{m}$ : Mass flow rate (kg/s)
LOX : Liquid oxygen
$p_a$ : Ambient pressure (Pa)
$p_o$ : Outlet pressure (Pa)
PMMA : Poly methyl methacrylate
PVC : Polyvinyl Chloride
RFNA : Red fuming nitric acid
$V_o$ : Outlet velocity (m/s)

## 1. INTRODUCTION

In technical usage, a missile is a projectile that moves with guidance, while a rocket is a projectile that is directed to a certain target and then moves without being guided. In daily use, both projectiles are called rockets. While rockets consist of stopper, warhead, propulsion system (rocket engine) and wings, missiles have a guidance and control system in addition to these elements. Rockets are generally used for defence purposes, civilian purposes, satellite launching, and orbiting and keeping the satellite in orbit[1]. Rocket engines are used for purposes such as space studies, defence industry (missiles such as Tomahawk, Javelin, Patriot, Stinger), land and sea vehicles and satellites[2].

According to the propulsion system used, rockets are classified as chemical fuel rockets, electric powered rockets, solar powered rockets and nuclear-powered rockets. The propulsion of chemical rockets is derived from the energy in the combustion reaction products[1]. Chemical propellant rockets are examined in three groups as solid propellant rockets, liquid propellant rockets and hybrid propellant rockets. In solid propellant rockets, fuel and oxidizer are mixed homogeneously to form a single piece of propellant material. In liquid fuel rockets, fuel and oxidizer are in liquid form in two separate tanks. With the combination of both, in the hybrid fuel rockets, the thrust is created by ejecting the exhaust gas, which is formed by the combustion of liquid or gaseous oxidizer and solid fuel by providing the required ignition temperature[3].

Due to the cost and complexity of liquid fuel rockets, the explosion hazard and thrust control problems of solid fuel rockets, more studies have been carried out on the use of hybrid rockets recently. With the reported advantages such as cost, relative ease of thrust control and safety in usage as well as in transportation of fuel[4-5], hybrid rocket engines are also preferred due to the fact that they are more convenient to manufacture, use and operate than others[6].

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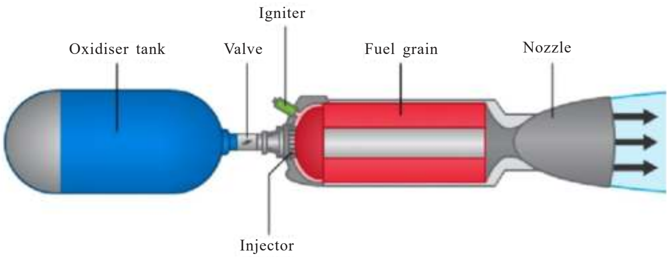



**Figure 1. A typical configuration of a hybrid rocket engine[7].**

**Figure 2. Spaceship spacecraft with hybrid rocket engine[9].**

The main components of hybrid rocket engines can be listed as oxidizer tank, valve, igniter, injector, fuel grain and nozzle as shown in Fig. 1[7].

Various analytical, numerical and experimental studies have been carried out on hybrid rocket engines, and they have extensive applications in many areas such as research rockets, attack drones, small launch vehicles and space vehicles[8]. Figure 2 shows one of the real life application examples related with topic, the Spaceship spacecraft that uses hybrid rocket engine.

Li[10], *et al.* investigated the impact of different fuel geometries on combustion rate through the utilisation of solutions to the Navier-Stokes equations, chemical reactions, and boundary layer problems. Additionally, they developed a transient numerical simulation model for variable thrust Hybrid Rocket engines, integrating gas-solid coupling, turbulent combustion, and dynamic mesh techniques. This model was validated through experimental trials on a hybrid rocket engine. Their findings indicate positive correlations between thrust, chamber pressure, and regression rate with oxidizer mass flow rate. Notably, they highlight the significant influence of vortex formation on regression rate distribution. These results offer insights for the design and optimization of Hybrid Rocket Motors (HRMs) under variable thrust conditions[10].

Existing literature suggests that altering the geometry of the solid fuel core yields a positive impact on the regression rate. Knuth[11], *et al.* conducted experiments utilising both laboratory-scale (89 N thrust) and larger-scale (445 N-890 N thrust) rocket engines, employing a methodology where the oxidizer was directed onto PMMA to induce vortex formation. Throughout these experiments, the fuel length of the combustion chamber and the average fuel core diameter were varied. This facilitated an examination of the effects of alterations in combustion chamber geometry on the regression rate. The authors observed a regression rate approximately 7 times higher than that of conventional hybrid rocket engines.

In the study conducted by Tian[12], *et al.* a helical geometry was introduced to the fuel surface, resulting in an increase in turbulent kinetic energy and the occurrence of eddies. This geometric modification led to an elevation in the regression rate. Additionally, the axial delivery of oxidiser to the combustion chamber contributed to this increase in regression rate. The presence of the spiral structure and the uneven fuel surface facilitated an increase in both eddy size and turbulence within the flow. Factors influencing the regression rate included the slope of the fuel core geometry, as well as the depth and width of the fuel core groove. Specifically, the slope contributed to a 40 % increase in the regression rate, while the depth and width led to in creases ranging from 15 % to 20 % and 10 %, respectively. One of the observed phenomena in this study was the formation of vortices in concave parts of the fuel geometry, as determined through numerical analysis. The authors asserted that both simulations and experimental tests corroborated the effectiveness of helical structures in augmenting the fuel regression rate, with geometric parameters such as groove depth and width also exerting influence on the rate of regression.

Whitmore[13], *et al.* conducted an investigation into cylindrical fuel geometry with varying helix ratios, resulting in observed positive changes in the regression rate corresponding to the helix ratio. Additionally, the study explored the correlation between Reynolds number and regression rate across different fuel geometries. Shan[14], *et al.* studied the scale effect in hybrid rocket engines, evaluating the impacts of axial length and fuel core diameter alongside combustion speed. It was observed that, with increasing length in the fuel core, the regression rate locally decreased after reaching a certain value. Furthermore, the authors determined that while an initial increase in the regression rate was observed with an increase in combustion chamber diameter, subsequent decreases in regression rate occurred. The study encompassed cylindrical, star, and wagon wheel fuel geometries, revealing a rapid decrease in regression rate from the starting point of the fuel core followed by a consistent increase towards the nozzle. Furthermore, an increase in oxidizer quantity resulted in augmented regression rates across all three fuel geometries, with the wagon and star-type geometries exhibiting notably greater increases.

Zhang[15], *et al.* investigated vortex fuel cores numerically and experimentally, noting a 60 % increase in regression rate compared to cylindrical fuel cores under identical conditions. Sun[16], *et al.* conducted numerical and experimental analyses by introducing obstacles into cylindrical fuel profiles, resulting in increased regression rates post-obstacle. Consequently, it was concluded that turbulence subsequent to the obstacle positively influenced the regression rate.

There is a limited number of experimental reports on hybrid rocket testing available in the literature. In this study, a hybrid rocket engine static ignition testing setup has been designed and fabricated to provide experimental support for researchers interested in conducting research on rocket engines. Within the scope of this study, a series of experimental trials were conducted using the custom testing apparatus to assess the variation of thrust over time. Thrust change was examined by changing the fuel geometry and the two fuels were compared.

PVC was used as fuel and Gaseous Oxygen (GOX) was used as oxidizer. The details on test setup and conduction of experiments were given. The effect of the fuel cavity geometry was evaluated by determining the thrust-time variation *F-t*, total impulse $I_t$, average thrust $F_{avg}$, maximum thrust $F_{max}$, specific impulse $I_s$ and effective exhaust gas velocity *c* values for the case of straight and square grooved fuel.

## 2. METHODOLOGY

### 2.1 Design Process

In this study, a hybrid rocket engine was produced and combustion experiments were carried out with different fuel geometries. Polyvinyl Chloride (PVC) material was chosen as the fuel whose performance will be determined, given its advantageous properties such as high energy content, ease of processing, cost-effectiveness, and controllable combustion characteristics. To investigate the effect of altering the geometry of PVC fuel on thrust, two different PVC fuel geometries, namely straight and square grooved, were designed and manufactured. Oxygen was chosen as the oxidizer due to its high reactivity and abundance. The geometric properties of the straight and square grooved fuels are presented in Fig. 3 and Fig. 4 (All measurements in these figures are in millimetres). The PVC fuel was initially obtained as a Ø80 solid rod material. It was processed on a lathe according to the desired dimensions. For the latter, square grooves were created using a suitable internal cutting tool. In Fig. 5, the initial states of these two different PVC fuels are depicted before the experiment.

Abell-shaped nozzle was chosen considering ease of production. The selection was made to accommodate PVC fuel. Dimensions were determined according to Sutton and Biblarz[17] (Fig. 6). The dimensions of nozzle are given in Fig.7.

#### *2.1.1 Experimental Setup*

The connection diagram of the experimental setup is shown in Fig.8.

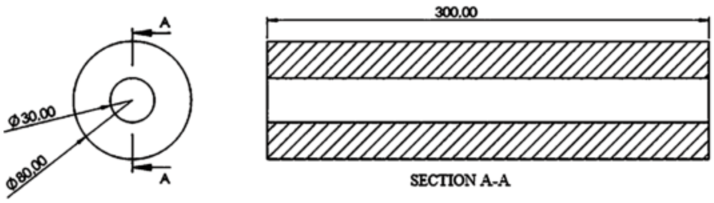



**Figure 3. Straight fuel geometry.**

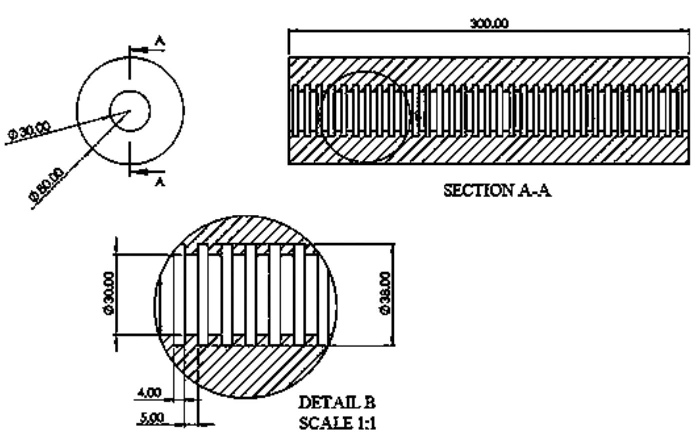



**Figure 4. Square grooved fuel geometry.**

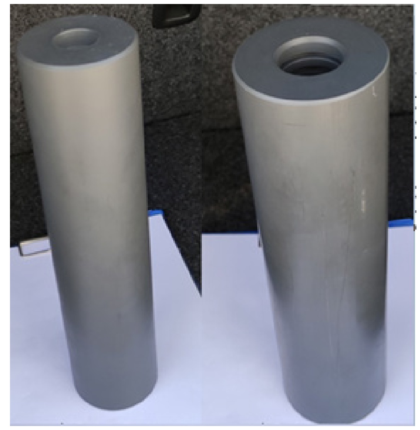


**Figure 5. Straight and square grooved fuels used in the experiment.**

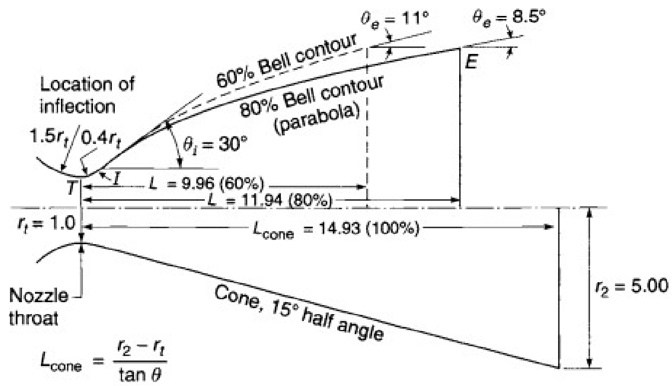



**Figure 6. Nozzle sizing[17].**

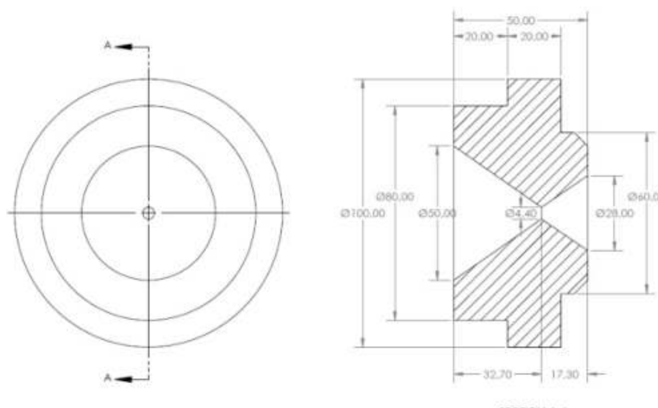



**Figure 7. Converging-diverging nozzle dimensions.**

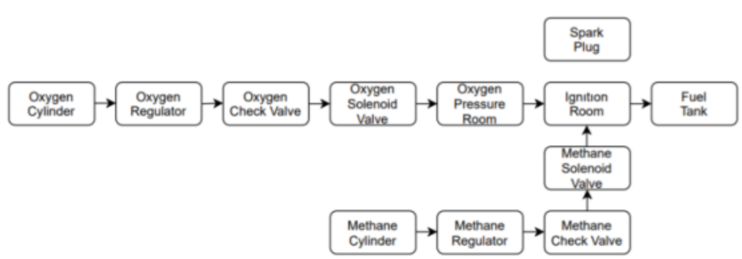


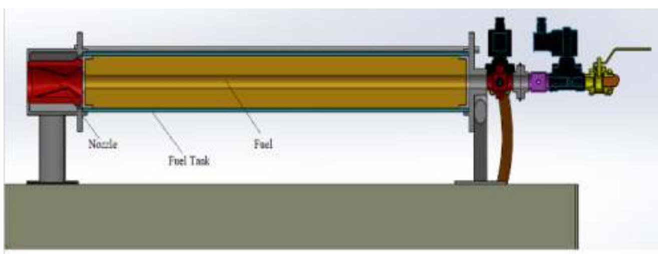

**Figure 8. Assembly connection diagram.**

The oxygen cylinder was employed as an oxidizer to facilitate the oxidation of the fuel core. The oxygen tube volume must meet a minimum requirement of 50 ltr, and its surface should be devoid of any defects such as roughness. Similarly, the methane gas cylinder was utilised to supply the ignition system and initiate combustion. The volume of methane tube should be at least 10 ltr and should be unused, with its surfaces free from imperfections like those of the oxygen cylinder.

An oxygen regulator was utilised to regulate the outlet pressure of the oxygen cylinder, constructed from brass material. The section designed as an orifice where combustion chamber and pressure sensors are installed is also manufactured from brass material. Brass material is commonly used in gas transmission due to its ease of production and processing, as well as its soft nature, which additionally ensures sealing. Ball valves, selected as flow control elements, are required to be of pipe type and suitable for fluid control. Solenoid valves, employed for oxygen and methane flow control and stainless steel body materials, with the latter possessing a linear shape. Check valves serve as flow control elements to prevent backflow.

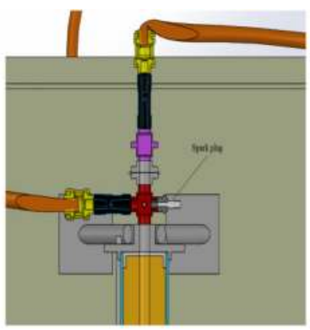
For the ignition system, an ignition coil and spark plug were integrated into the assembly. The chassis of the test rig was constructed using 30mmx30mm aluminium profiles, while steel blocks were employed in nozzle production. O-rings functioned as sealing elements within the system.

Computer aided design of the combustion chamber, oxygen and methane tube, spark plug and ignition system are shown in Fig. 9(a), Fig. 9(b) and Fig. 9(c), respectively.




(a)

(b)




(c)

**Figure 9. Computer aided design of (a) Combustion chamber. (b) Oxygen and methane cylinder, and (c) Spark plug and ignition system.**

The gas coming from the oxygen cylinder goes to the ball valve for safety purposes, by determining the pressure from the oxygen regulator. Oxygen gas coming out of the ball valve is restricted to return with a check valve for safety purposes and enters the experiment setup through the solenoid valve with computer aided control. In the oxygen pressure chamber, the oxygen flow rate is calculated using Bernoulli's Equation. Simultaneously, the igniting gas coming out of the methane cylinder enters the methane ball valve for control purposes through the methane regulator. As with oxygen gas, methane enters the ignition chamber through the solenoid valve which provides computer-aided control. The oxygen gas and methane, which meet in the ignition chamber, burn with the ignition of the spark plug and the methane gas transmission is cut off. The resulting fire enters the test fuel tank with the oxygen

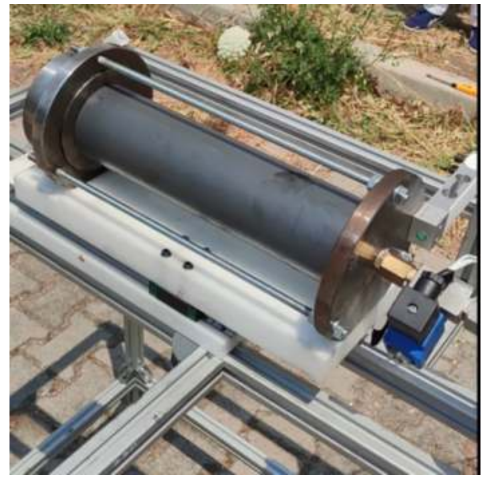
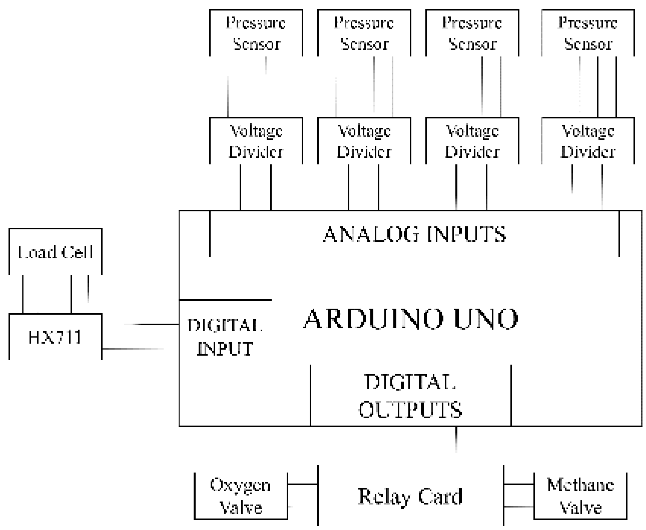
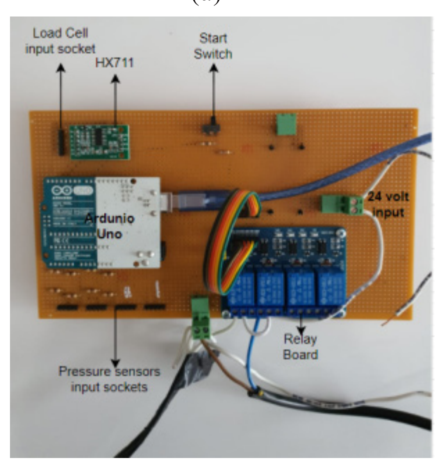


**Figure 10. Final state of the experiment system (engine, oxygen inlet and load cell).**




(a)




(b)

**Figure 11. (a) Electronic circuit conceptual design, and (b) Electronic system on perforated copper plate.**

pressure and combustion occurs in the combustion chamber. The exhaust gas formed as a result of combustion is thrown into the atmosphere through the nozzle. The thrust created by this gas released into the atmosphere is measured by the load cell on the experimental setup.

The entire rocket system can move on the bed and the thrust created by stopping it by the flange is measured by the load cell (Fig. 10) positioned adjacent to the cylindrical part to which the fuel is connected before the test begins.

#### *2.1.2 Data Collecting*

To collect data with respect to specific time during conduction of the experiment, an electronic board including necessary components such as a suitable microcontroller, sensors and required integrated circuits is designed and built. It is considered power management for diverse sensors and electronic valves. In the experimental setup, a load cell with HX711 digital amplifier and pressure sensors are considered as data collecting (input) devices. Electronic valves with electronic relay board that control the inlet of oxygen and methane gas are considered as output devices. Overall, there are two electronic valves to be controlled, four pressure sensors and a load cell to be digitized and read. Arduino UNO has been found appropriate to use as a microcontroller, considering the ease of use and accessibility. Conceptual design of electronic circuit with necessary connections and built circuit are shown in Fig. 11(a) and Fig. 11(b).

In order to record the processed data comes from Arduino in real time, a desktop application based on .NET architecture is created, where communication is utilized with USB interface. Thanks to embedded software in Arduino, desktop application and given hardware, automatic calibration and resetting operation of load cell takes place at the beginning.All experiment procedure is automated and data is recorded to be processed later.

### 2.2 Experimental Procedure

The first experimental setup is given in Fig. 12. Initial ignition was achieved manually, and flow rates were obtained by measuring the initial and final pressures of the oxygen cylinder and the initial and final weights of the fuel. The thrust was measured with the load cell. The photographs taken during the experiment are shown in Fig. 13.

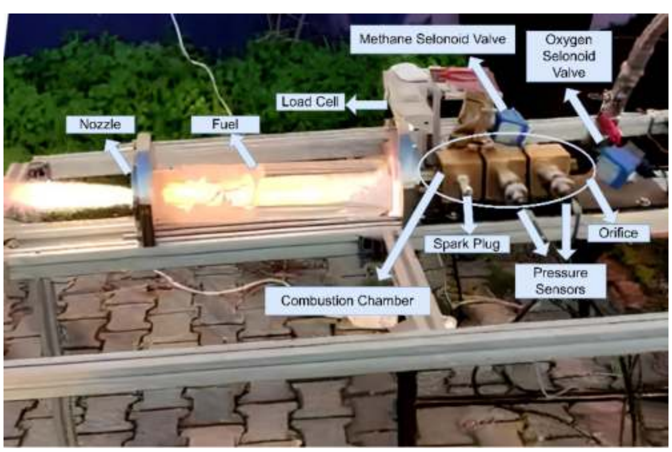



**Figure 12. Appearance of the experimental equipment used in the first set of experiments.**

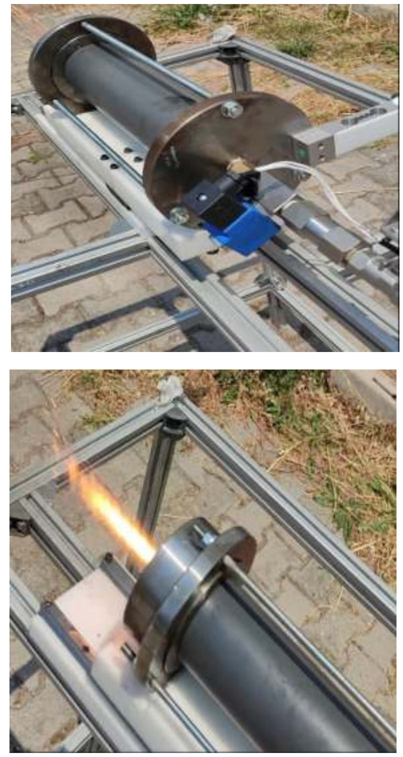


**Figure 13. Views during the experiment.**

## 3. RESULTS AND DISCUSSION

The effect of the fuel cavity geometry was evaluated by determining the thrust-time variation *F-t*, total impulse $I_t$ (Eqn.1), specific impulse $I_s$ (Eqn.2), average thrust $F_{avg}$ and maximum thrust $F_{max}$ (Eqn.3) and effective exhaust gas velocity *c* (Eqn. 4), values for the case of straight and square grooved fuel. These quantities are computed using following Eqn.[18]. Values are listed in Table 1.

$$I_t = \int_o^{t_s} F dt \quad (1)$$

$$I_s = \frac{\int_o^{t_s} F dt}{g \int_o^{t_s} \dot{m} dt} \quad (2)$$

$$F = \dot{m} V_o + (p_o - p_a) A_o \quad (3)$$

$$c = \frac{\int_o^{t_s} F dt}{\int_o^{t_s} \dot{m} dt} \quad (4)$$

**Table 1. Results for straight fuel and square grooved fuel**

| | Straight fuel | Square grooved fuel |
|---|---|---|
| O/F | 1.97 | 1.60 |
| $F_{avg}$ (N) | 10.06 | 14.37 |
| $F_{max}$ (N) | 10.82 | 16.08 |
| $I_t$ (Ns) | 155.95 | 237.02 |
| $I_s$ (s) | 123.23 | 203.03 |
| c (m/s) | 1208.87 | 1991.74 |
| $m_{f,initial}$ (kg) | 1.800 | 1.722 |
| $m_{f,final}$ (kg) | 1.671 | 1.603 |

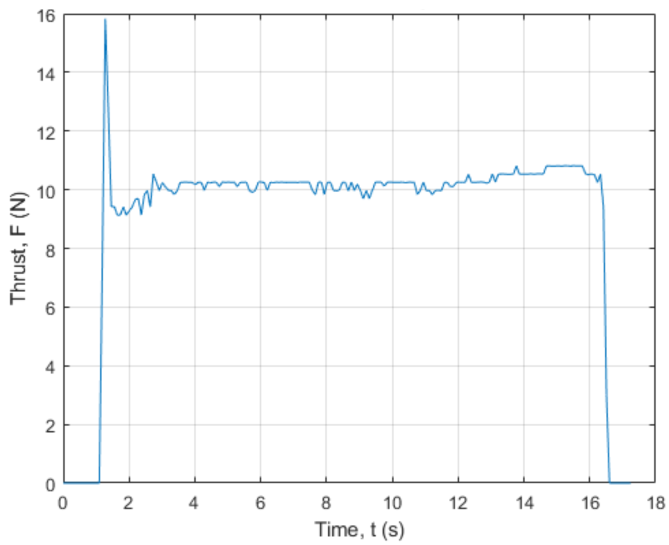



**Figure 14. Thrust-time graph obtained as a result of the experiment (Straight fuel).**

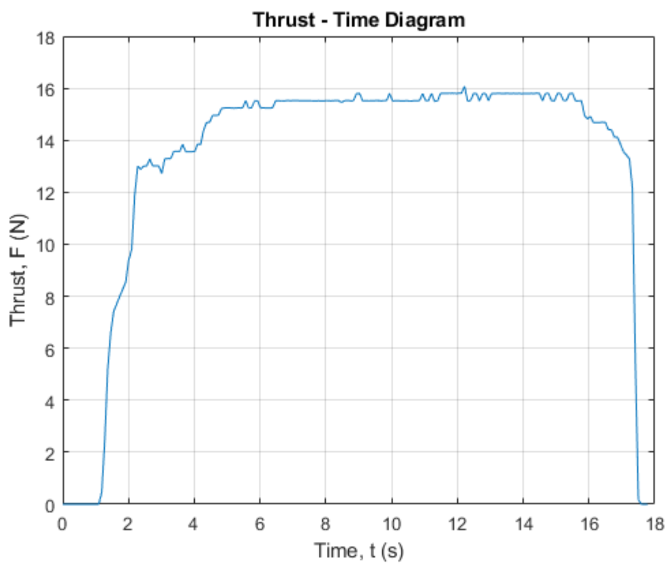



**Figure 15. Thrust-time graph obtained as a result of the experiment (Square grooved fuel).**

O/F ratio is defined as[19]:

$$\mathbf{O/F} = \frac{\dot{m}_{ox}}{\dot{m}_f} \tag{5}$$

Burning time of straight fuel with circular inner hole was 15.5 s, and combustion time of fuel with square inner hole was 16.5 s. Thrust-time diagrams for straight fuel and square grooved fuel are given in Fig.14-15. The obtained thrust-time graph exhibits similarity with the thrust-time graph obtained in a study found in the literature[20].

Table 2 shows the specific impulse and O/F ratios for various fuels and oxidisers. Upon comparing the specific impulse values of 230 s and 290 s given for PVC in Table 2 with the 123.23 s value obtained from the study, it is apparent that the value derived from the study is lower.

In the literature, the composition of solid fuel is often highlighted as a genuine concern in hybrid propulsion technology. Solid fuel developments typically focus on materials such as HTPB, which are commonly regarded as reference materials due to their superior thrust performance and regression rate. Paraffin and most polymers exhibit similar performance characteristics (e.g., HTPB, CTPB, PBAN as thermoset polymers, or PE, PU, or DCPD as thermoplastics). However, fuels such as PMM, PU, PBL, and PVC perform relatively poorer in terms of propulsion efficiency[21].

**Table 2. Typical fuels and oxidisers[22]**

| Fuel | Oxidiser | O/F | $I_{sp}$(s) |
|---|---|---|---|
| HTPB | LOX | 1.9 | 280 |
| PMMA($C_5H_8O_2$) | LOX | 1.5 | 259 |
| HTPB | $N_2O$ | 7.1 | 247 |
| HTPB | $N_2O_4$ | 3.5 | 258 |
| HTPB | RFNA | 4.3 | 247 |
| HTPB | FLOX($OF_2$) | 3.3 | 314 |
| Li/LiH/ HTPB | FLOX($OF_2$) | 2.8 | 326 |
| PE | LOX | 2.5 | 279 |
| PE | $N_2O$ | 8.0 | 247 |
| Paraffin | LOX | 2.5 | 281 |
| Paraffin | $N_2O$ | 8.0 | 248 |
| Paraffin | $N_2O_4$ | 4.0 | 259 |
| HTPB/Al(%40) | LOX | 1.1 | 274 |
| HTPB/Al(%40) | $N_2O$ | 3.5 | 252 |
| HTPB/Al(%40) | $N_2O_4$ | 1.7 | 261 |
| HTPB/Al(%60) | FLOX($OF_2$) | 2.5 | 312 |
| Cellulose ($C_6H_{10}O_5$) | GOX | 1.0 | 247 |
| Carbon | Air | 11.3 | 184 |
| Carbon | LOX | 1.9 | 249 |
| Carbon | $N_2O$ | 6.3 | 236 |
| PVC | GOX | 4 | 230 |
| PVC | GOX | 2 | 290 |

One of the most important results of this project is that when straight fuel and square grooved fuel are compared, using square groove in the fuel cavity provides 48.6 % improvement in maximum thrust, 52 % in total impulse, 64.8 % in specific impulse and 64.8 % in effective exhaust speed. This improvement was achieved by changing the geometry, especially by increasing the combustion surface.

## 4. CONCLUSIONS

Within the scope of the study, a hybrid rocket engine static ignition testing setup was designed and produced. Experiments were carried out using this setup for both for straight and square grooved fuel. As a result of the experiments, the thrust-time variation of the PVC/Oxygen fuel/oxidiser was determined for straight and square grooved fuel. It has been shown that selecting a fuel cavity geometry that increases the surface area results in an increase in thrust. As a result of experiments aiming to compare the performances of straight fuel and square grooved fuel configurations, it was found that using a square groove in the fuel cavity provides a 48.6 % increase in maximum thrust, a 52 % increase in total thrust, a 64.8 % improvement in specific thrust and a 64.8 % increase in effective exhaust velocity.

Various sources of experimental uncertainty are present in the current work. The choice of fuel, human errors in production and assembly, inadequate oxygen supply due to mistakes, errors in nozzle design, low pressure, ignition issues, among others, have led to inefficient combustion resulting in low thrust, such as 10 N. Conducting simulations, performing tests, and optimizing various regions of the rocket will help identify and address the underlying causes of low thrust output.

The prepared test setup will serve as a platform for conducting experiments and numerical analyses on various fuel geometries in future studies. These forthcoming investigations aim to evaluate the performance of different fuel configurations. In this context, the flexibility and precision offered by the test setup will contribute significantly to future research endeavours.

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