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Computational Investigation of Combustion Efficiency in LOX-HTPB Hybrid Rocket Motors

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Abstract: Hybrid rocket engines that use hydroxyl-terminated polybutadiene (HTPB) fuel and liquid oxygen (LOX) oxidiser are appealing because they are safe, work well, and are good for the environment. Nevertheless, combustion efficiency is still low because the oxidiser and fuel are not mixed well enough. This study offers a computational and experimental analysis of the internal ballistics of LOX–HTPB hybrid motors, focusing on injector design and chamber flow dynamics. CFD simulations validated with experimental data were used to compare swirl and pintle injectors to baseline injectors. The results show that pintle and tangential swirl injectors make combustion more efficient by improving the distribution of oxygen, turbulence, and pressure uniformity. The results show how to make the design of injectors and chambers better in hybrid propulsion systems.

Table of Contents

1. Introduction

Hybrid rocket propulsion systems that combine solid fuel with a liquid oxidizer have attracted interest due to their simplicity and safety compared to fully liquid or solid rockets. Hydroxyl-terminated polybutadiene (HTPB) mixed with liquid oxygen (LOX) has garnered considerable interest due to its relatively high specific impulse (≈250–320 s), straightforward storage, and safe, non-toxic components [4],[5] This can lead to incomplete combustion and reduced performance. The primary cause is inadequate mixing of pyrolyzed fuel and oxidiser in the chamber [1]. The oxidiser must diffuse into the fuel's boundary-layer pyrolysis zone before reacting, a process that inherently limits the regression rate and efficiency [4]. Key design factors, including the oxidiser-to-fuel (O/F) ratio, fuel port geometry, chamber configuration, and injector design, strongly influence the mixing and combustion process [1],[2],[3]. Many approaches have been proposed to enhance mixing and fuel regression (for example, specialised injector geometries, flow turbulators, or modified grain ports) [1],[2]. However, a comprehensive understanding of how these features affect combustion efficiency under different operating conditions remains lacking [1],[2]. This study addresses these challenges by developing a high-fidelity CFD model of a LOX–HTPB hybrid rocket motor and using it to analyse the effects of design parameters on internal flow and performance. Specifically, the influence of injector geometry (e.g., swirl and pintle injectors), post-chamber geometry, and varying O/F ratios on mixing and efficiency is examined. To guide the investigation, the main objectives are:

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- Model Development and Validation: Build and validate a CFD model for LOX–HTPB combustion.
- Injector Design: Evaluate swirl injector configurations (including tangential-entry and helical designs) and compare them with baseline injectors to improve oxidiser distribution [6][11].
- Chamber and Nozzle Design: Design and optimise the combustion chamber and De Laval nozzle using CFD insights.
- Performance Analysis: Analyse pressure, temperature, species, and turbulence fields for different O/F ratios to identify trends in combustion efficiency.

This research has a goal to find configurations that improve mixing and bring combustion efficiency closer to the 0.95+ range, that is typical of the best hybrids by systematically studying these factors [15].

2. Literature Review

2.1 LOX–HTPB Hybrid Rocket Motors

Hybrid rockets use a solid fuel and a liquid or gas oxidiser to get the best of both solid and liquid propulsion systems [4]. LOX–HTPB is one of the best hybrid propellant combinations because it works well and has many other benefits [4][5]. It has a specific impulse of about 250–320 s, which is similar to many storable liquid propellants [4][5]. HTPB, on the other hand, is mechanically strong and non-toxic. Even though LOX–HTPB systems have these benefits, they have a big problem: the combustion process is limited by diffusion [4][7]. The oxidiser must first get through the fuel's boundary layer and mix with the vaporised fuel before it can react. This means that the regression rate is limited. This often results in suboptimal combustion efficiency. Therefore, much research has focused on internal ballistics improvements - chiefly enhancing oxidizer-fuel mixing - to raise thrust and efficiency [1][2].

2.2 Injector Design in Hybrid Motors

The injector’s role is to distribute and atomize the oxidizer while inducing turbulence for mixing. Several injector configurations have been investigated:

Swirl Injectors- Swirl injectors impart angular momentum to the oxidizer flow, creating strong vortices and recirculation zones near the chamber inlet [6]. This vortex flow significantly boosts radial mixing and flame anchoring. Karabeyoglu et al. demonstrated that a swirl (vortex) injector can markedly increase hybrid fuel regression rates by enhancing convective heat flux to the fuel surface [6]. The intense turbulence induced by swirl injectors is particularly effective for LOX–HTPB, promoting rapid entrainment of oxidizer into the boundary layer.

Shear Coaxial Injectors- In a shear-coaxial design, an inner jet of one fluid (e.g. fuel) is surrounded by an annular flow of the other (e.g. oxidizer), or vice versa. The velocity difference at the shear layer generates interfacial turbulence and atomization [7]. Such injectors are common in liquid engines and have been adapted for hybrid motors in high-thrust applications. The shear forces can enhance mixing, but their effectiveness in fully driving radial mixing in hybrids is still under study [7].

Showerhead Injectors- Showerhead injectors consist of multiple straight-through orifices that spray oxidizer uniformly across the fuel grain. This simple geometry is easy to manufacture and provides even fuel coverage, making it suitable for low-thrust motors. However, because each port produces mostly axial flow, turbulence generation is limited [4]. As a result, regression rate improvement from showerhead injectors is typically modest.

In this study, a **swirl injector configuration** is selected for detailed analysis due to its proven ability to generate turbulence and uniform mixing in LOX–HTPB rockets [11]. Variants such as tangential-entry swirl injectors and helical-ramp swirl injectors (which introduce additional angular momentum) will be evaluated for performance optimization [11].

2.3 Combustion Chamber and Nozzle Design

2.3.1 Combustion Chamber

The combustion chamber must withstand typical LOX–HTPB operating pressures (≈10-40 bar) [5]. Chamber geometry influences flame stability and oxidizer residence time. For example, the cross-sectional shape of the fuel port (circular, star-shaped, helical, etc.) affects how boundary-layer vortices develop and how the regression rate evolves [4]. Circular ports are often used in initial designs and CFD studies for their axisymmetric and simplicity [4]. Other shapes (star or helical) can increase surface area or induce secondary flows, but their effects must be evaluated case by case.

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2.3.2 Nozzle

A convergent–divergent (De Laval) nozzle is utilized to accelerate the hot combustion gases to supersonic velocities, generating thrust. Important nozzle parameters comprise the expansion ratio (exit area/throat area) and the divergence angle. Typical expansion ratios for hybrid rockets range from about 5 to 20, depending on whether sea-level or vacuum performance is desired [8]. The throat size and nozzle contour are usually determined by one-dimensional isentropic flow relations for the desired chamber pressure and thrust [8]. The design of the nozzle plays a crucial role in determining the exhaust velocity and the overall thermal efficiency of the propulsion system.

2.4 Turbulent Mixing and Regression Rate Models

The rate at which the solid fuel regresses (burns away) depends on convective heat flux from the flame to the fuel surface and the subsequent pyrolysis process [4]. A widely used empirical correlation for the regression rate is of the form:

$$\dot{r} = a\,G_o^n,$$

where $\dot{r}$ is the surface regression rate, G_o is the oxidizer mass flux, and a, n are empirical constants [4][7]. For LOX–HTPB, typical values of a and n have been reported in the literature. Advanced models further include corrections for blowing (mass flux of pyrolysis products) and detailed chemical kinetics in the boundary layer [8]. Such models often require CFD to resolve the flame structure and species diffusion. Finite-rate combustion models, coupled with species transport equations, can capture the interaction between vaporized HTPB and LOX in the chamber, yielding more accurate predictions of $\dot{r}$ under various conditions [8].

2.5 CFD Modeling Techniques for Hybrid Combustion

Computational fluid dynamics (CFD) is a powerful tool for analyzing internal flows in hybrid motors and guiding design before experiment [9].

2.5.1 Governing Models

Typical simulations use steady Reynolds-Averaged Navier-Stokes (RANS) equations with turbulence models such as standard k -ε or k -ω SST [9]. For higher fidelity, Large Eddy Simulation (LES) may be employed. Combustion is generally modeled as a non-premixed (diffusion) flame with finite-rate chemistry. Species conservation equations are solved for the oxidizer and fuel vapor (from HTPB), with appropriate source terms for reaction [9][10]. This approach can capture the coupling between flow turbulence and combustion.

2.5.2 Boundary Conditions and Meshing

The computational mesh must be fine enough to resolve boundary layers at the fuel surface and shear layers at injector ports [9]. Commonly applied boundary conditions consist of prescribing either a mass-flow rate or velocity at the oxidizer inlet (injector), enforcing no-slip adiabatic or heat-transfer constraints on the chamber and injector walls, and imposing a pressure outlet at the nozzle exit, typically defined as ambient or vacuum conditions.Wall functions or conjugate heat transfer models can be applied to model the fuel regression and wall heating if needed[9].

2.5.3 Validation

CFD results should be validated against experimental measurements whenever possible. Key validation metrics are chamber pressure profiles, thrust/time curves, and measured regression rates. Optical diagnostics (schlieren imaging or chemiluminescence) in experiments can also verify flame shape and mixing patterns predicted by the model [12].

2.6 Design Parameters and Operational Guidelines

2.6.1 Number of Injectors

The number of injector ports N the total oxidizer flow is delivered at the desired mass flux. For a port of area A_{inj} and injection velocity v_o , the parameter N can be estimated as $\dot{m}_o/(\rho_o A_{\text{inj}} v_o)$, where $\dot{m}_o$ denotes total oxidizer mass flow and ρ_o represents oxidizer density (≈1141 kg/m³ for LOX) [8].

2.6.2 Operational Pressure

Typical chamber pressures for LOX–HTPB motors are in the range 10–40 bar [5]. The actual pressure depends on the injector flow rate, the desired thrust level, and the nozzle expansion ratio. Structural limits of the chamber and cooling requirements also constrain the maximum allowable pressure [5].

2.6.3 Nozzle and Performance Parameters

Important performance parameters include the characteristic velocity C^* , specific impulse I_{sp} , and expansion ratio. These are determined by the propellant properties, throat area, exit area and combustion chamber pressure. Standard isentropic flow relations and combustion thermochemistry are used to compute C^* and I_{sp} for design purposes [4].

2.7 Summary and Research Gap

Extensive studies have investigated various elements of hybrid rockets – including injector designs, regression relationships, and CFD analyses of combustion – yet the majority of research examines components separately [4] [12]. Additionally, much previous research emphasizes non-cryogenic oxidizers (such as nitrous oxide), which might not directly apply to LOX-based systems. Integrated studies that merge validated CFD modeling with experiments for LOX–HTPB motors are scarce. In order to tackle these shortcomings, this study:

- Assesses swirl injector setups (comprising pintle and tangential-swirl types) to improve mixing.
- Develops and enhances the combustion chamber and nozzle shape using CFD analysis.
- Employs validated simulations to examine the internal flow (pressure, temperature, species, turbulence) and enhance overall LOX–HTPB combustion efficiency

3. Methodology

To methodically examine internal ballistics and mixing efficiency, six various LOX–HTPB hybrid motor setups were studied. These setups differed in fuel grain and casing sizes, alongside injector geometries, yet maintained consistent basic nozzle dimensions. Table 1 outlines the geometric details of the casing and fuel grain for each of the six configurations

Table 1: Motor casing and fuel grain dimensions for all configurations

Parameter in mm	1: Coaxial swirl injector	2: Coaxial swirl injector	3: Coaxial swirl injector	4: Coaxial swirl injector	5: Pintle injector	6: Tangential swirl injector
Casing inner diameter	50	50	50	70	50	50
Casing thickness	10	10	10	10	10	10
Casing length	210	210	377	175	175	175
Fuel grain inner diameter	15	15	15	20	15	15
Fuel grain outer diameter	50	50	50	70	50	50
Fuel grain length	150	185	352	150	150	150

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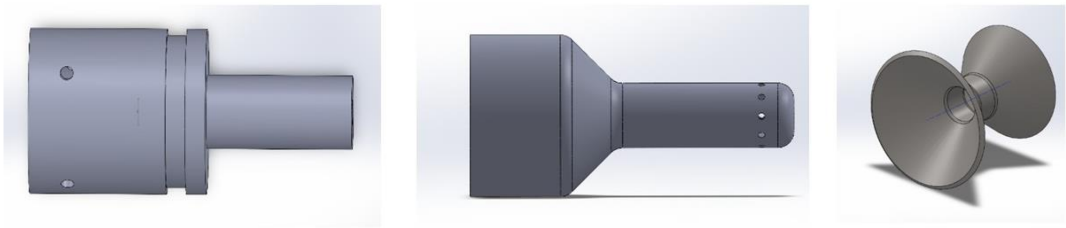
All motors employed a standard de Laval nozzle with a throat length of 10 mm, a throat radius corresponding to the geometry in Table 1, a converging section of 20 mm, a diverging section radius of 25 mm, and a shell thickness of 2 mm. Both the converging and diverging sections were 20 mm in length.

3.1 Injector Configurations

Three injector types were studied: coaxial swirl, tangential swirl, and pintle injectors.

- **Tangential swirl injector:** back wall radius 42 mm, mixing chamber 69 mm, convergent section 10 mm, nozzle radius 6.7 mm with 70 mm length, and 3.3 mm inlet ports [a].
- **Pintle injector:** back wall radius 25 mm, convergent section 22 mm, nozzle length 48 mm with 10 mm radius, and outlet ports 2 mm in diameter [b].
- **Coaxial swirl injector:** back wall radius 30 mm, mixing chamber 39 mm long, convergent section 20 mm, nozzle length 40 mm with 10 mm radius, and 10 mm inlet ports [c].

The injector and nozzle designs are shown schematically.



a b c

Figure 1: Injector Design- a. Tangential swirl, b. Pintle, c. Coaxial swirl

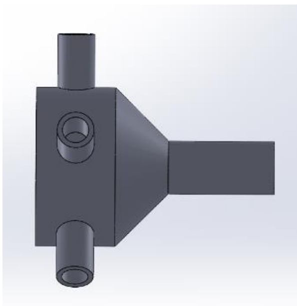


Figure 2:Nozzle design

3.2 CFD Modeling Techniques

Computational fluid dynamics (CFD) served as the primary tool for analysing internal ballistics and injector performance. To avoid numerical instability, the inlet velocity was set to 40 m/s with an oxidizer temperature of 90 K, corresponding to liquid oxygen. The outlet boundary was modelled with a gauge pressure of 1 atm. Steady-state Reynolds-Averaged Navier–Stokes (RANS) equations were solved with the k–ω SST turbulence model. Combustion was treated using a non-premixed flame model with finite-rate chemistry and species transport equations for vaporized HTPB and LOX. For higher fidelity, Large Eddy Simulation (LES) may be considered in future studies [6], [7]. A body-size mesh was generated with refinement at the injector inlets, fuel surface, and nozzle throat to resolve shear and boundary layers. Boundary conditions included: LOX mass flow inlet, no-slip adiabatic walls, and pressure outlet at the nozzle exit. Wall functions and conjugate heat transfer were applied to capture surface heat fluxes [6]. The completed mesh was exported to ANSYS Fluent, where simulations were performed.

3.3 Post-Processing

Contour plots of oxygen mass fraction, total pressure, total temperature, and turbulence kinetic energy were extracted for all six configurations. These outputs enabled comparison of flow mixing and combustion behaviour between injector types and geometrical variations.

4. Results and Discussion

4.1 Oxygen Mass Fraction

For configurations 1–4 (baseline and swirl variants without specialized geometry), the oxygen mass fraction contours show that the oxidizer is concentrated primarily near the injector inlet. Little oxygen persists further downstream in the chamber or nozzle (consistent with rapid consumption). This behavior is expected: the LOX is introduced at the injector and then consumed along the flow (refer figure 3-6).

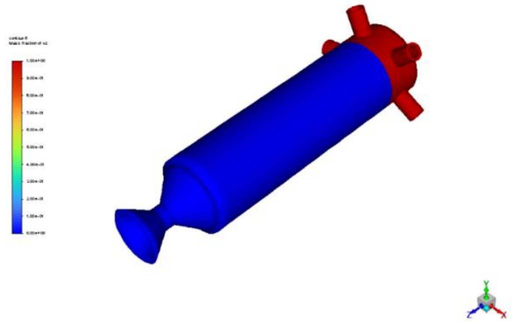


Figure 3: Configuration 1 Oxygen mass fraction

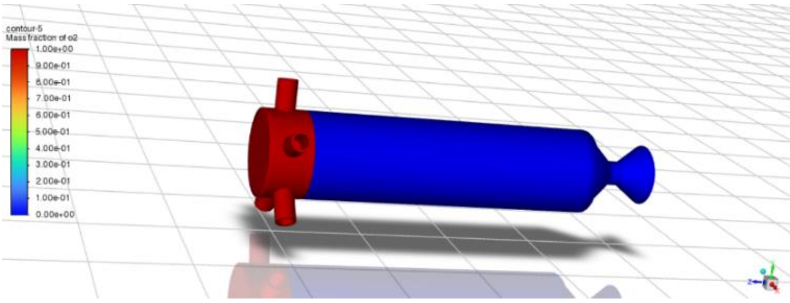


Figure 4: Configuration 2 Oxygen mass fraction

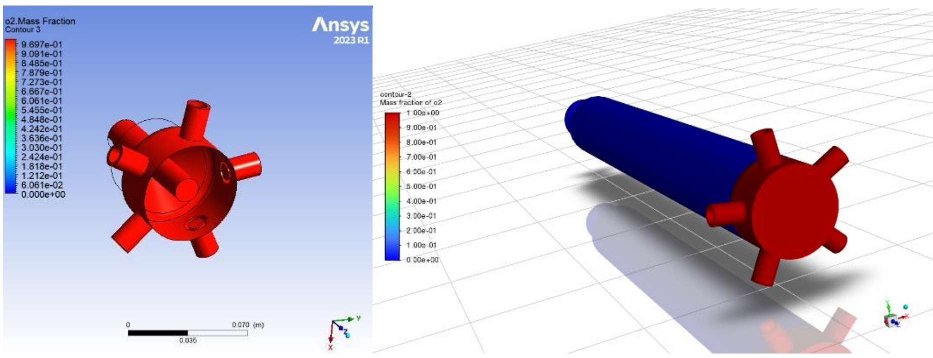


Figure 5: Configuration 3 Oxygen mass fraction at injector + whole motor

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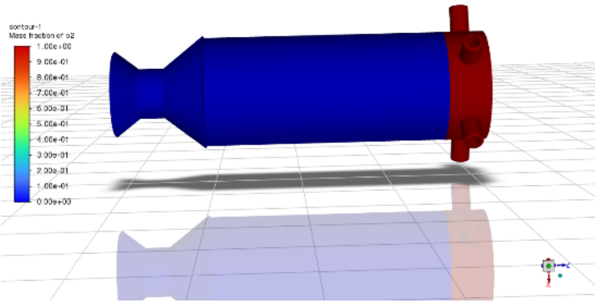

Figure 6: Configuration 4 Oxygen Mass Fraction

In contrast, Configuration 5 (pintle injector) distributes oxygen more uniformly throughout the chamber. The pintle's radial injection allows LOX to spread effectively into the core flow, improving mixing. Configuration 6 (tangential-entry swirl injector) similarly shows an expanded oxygen region due to the strong vortex flow it induces. In both Configurations 5 and 6, the oxidizer penetrates deeper into the chamber, indicating that these designs enhance mixing between LOX and the HTPB fuel. This improved oxidizer distribution suggests higher potential combustion efficiency for these configurations [6][11].

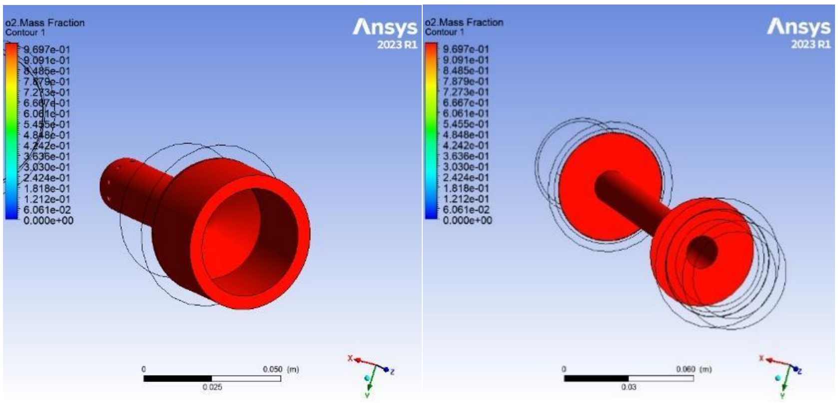

Figure 7: Oxygen mass fraction for configuration 5 motor casing and injector

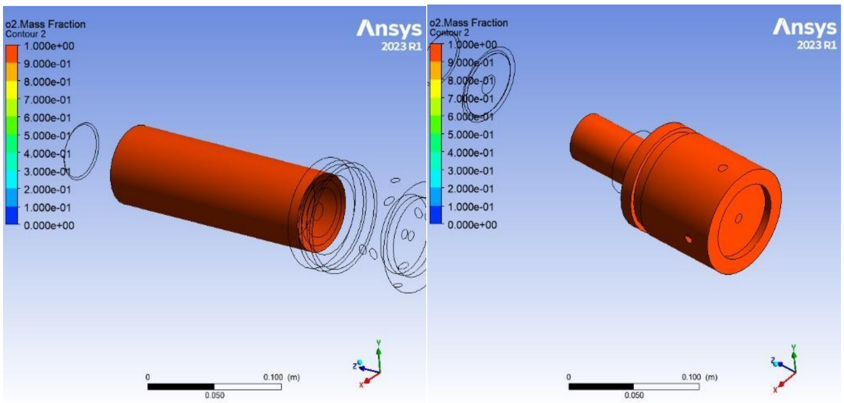

Figure 8: Oxygen mass fraction for configuration 6 injector and motor casing

4.2 Pressure Distribution

In Configuration 1 (straight injector), the total pressure is greatest at the injector inlet and diminishes downstream (through the chamber to the nozzle), as illustrated in Figure 9.

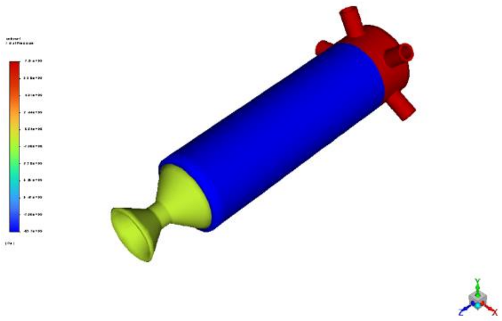

Figure 9: Total pressure contour configuration 1

This pattern reflects the high stagnation pressure from the inlet flow and the relatively confined expansion into the chamber. Configuration 2 (standard swirl injector) also shows pressure concentrated at the injector with little pressure downstream, indicating that expansion in the nozzle is not as efficient (see Figure 10).

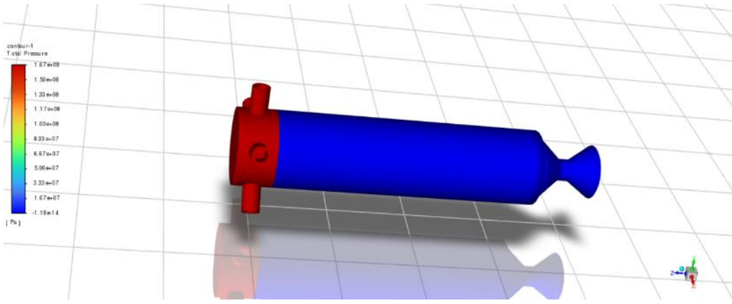

Figure 10: Total pressure contour configuration 2

Configurations 3 and 4 (swirl variants) exhibit a more uniform pressure field downstream: the pressure peaks are at the injector ports, but pressure decays more gradually through the chamber. This suggests smoother gas expansion and less abrupt pressure drop (see Figure 11 – Configuration 3).

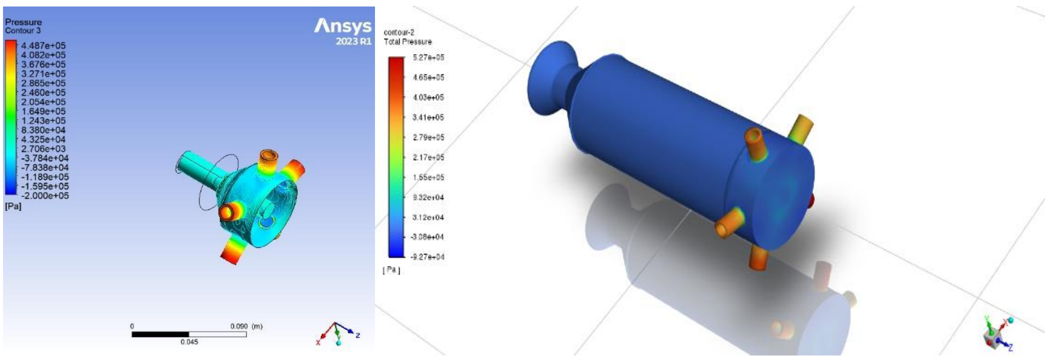

Figure 11: Total pressure contour Configuration 3 Injector

In Configuration 5 (pintle), the pressures in the chamber and nozzle are significantly elevated, showing a notable gradient at the injector–chamber boundary (refer to Figure 12). This gradient signifies robust mixing areas created by recirculation between the pintle and chamber. Ultimately, Configuration 6 (tangential swirl) exhibits maximum pressure at the injector ports along with a mild axial gradient leading to the nozzle (refer to Figure 13). The existence of elevated pressure at the inlets and turbulence caused by swirling suggests improved mixing and a more consistent pressure distribution within the motor.

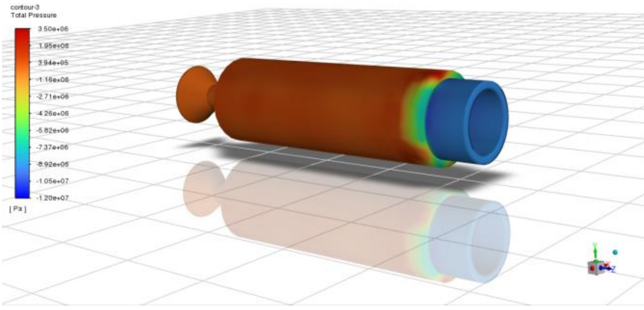

Figure 12: Total pressure contour configuration 5

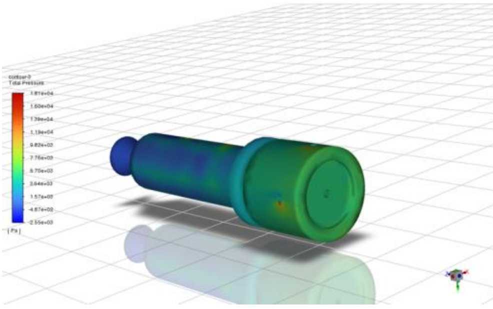

Figure 13: Total pressure contour configuration 6

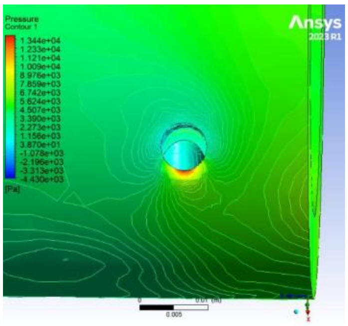

Figure 14: Inlet port of configuration 6

4.3 Temperature Distribution

In Configuration 1, the greatest temperatures are found in the combustion chamber (where chemical energy is generated) and decrease in the injector and nozzle. Configuration 2 reaches its maximum temperature at the chamber exit, decreasing along the nozzle as the gas expands. In Configuration 3, the chamber once more displays the peak temperature, with a moderately high temperature in the nozzle caused by the accelerating flow, while the injector stays cold (LOX at 90 K). Total temperature contours for Configuration 3 (Figure 15) and Configuration 4 (Figure 15) show that Configuration 4 exhibits a profile similar to Configuration 3 yet features a steeper temperature decline in the nozzle area. The more pronounced slope in Config. 4 indicates a greater expansion ratio (and consequently more effective cooling through expansion) in comparison to Config.

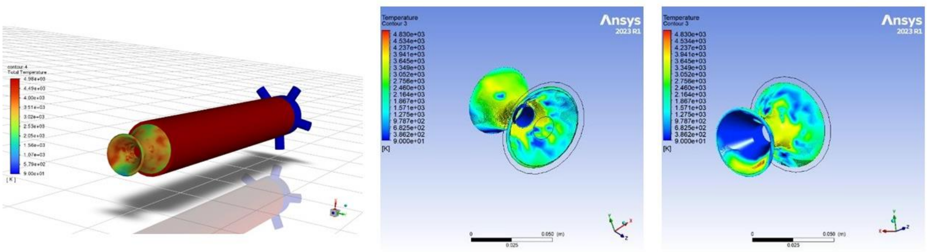

Figure 15: Total temperature contours for Configuration 3

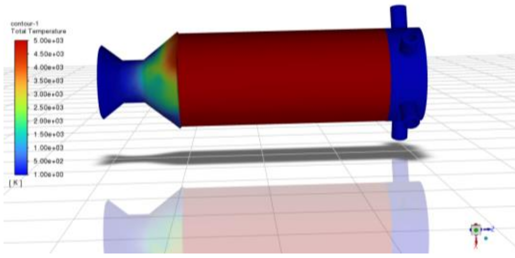

Figure 16: Total temperature contours for Configuration 4

Configuration 5 (pintle injector) displays the maximum temperature occurring closer to the nozzle, rather than immediately downstream of the injector. This implies that the combustion has been stabilized in a recirculation zone and is delayed downstream. Studies have shown that pintle injectors tend to form a central recirculation region that can shift the flame away from the injector face [11]. A similar effect is seen in Configuration 6: the hottest region is near the nozzle, indicating combustion occurs further downstream. In both Configs. 5 and 6, the combustion zone appears to be distributed deeper in the chamber, which is consistent with the enhanced mixing and flame stabilization provided by these injector designs. Figure 17 – Total temperature contours for Configuration 5 (pintle) and Configuration 6 (tangential swirl).

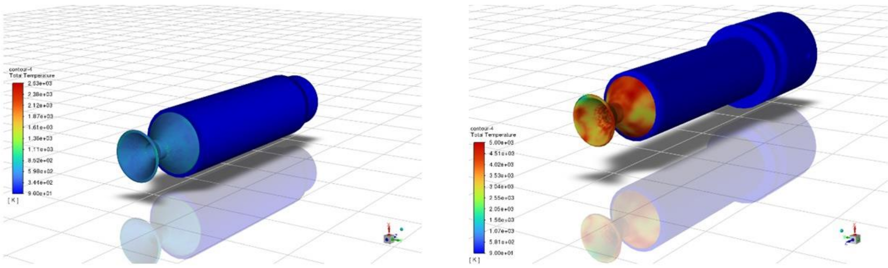

Figure 17: Total temperature contours for Configuration 5 (left) and Configuration 6 (right)

4.4 Turbulence Kinetic Energy

Configuration 1 produces moderate turbulence: TKE is elevated near the chamber (due to the combustion plume) and decays toward the nozzle, but only the injector region generates turbulence. In Configuration 2, the TKE is mostly confined to the injector ports, with minimal turbulence in the chamber. This indicates that oxidizer–fuel interaction is happening primarily at the inlet and not sustained downstream.

Configurations 3 and 4 show the highest TKE levels at the injector port junction (where multiple inlets meet), as seen in Figure 18 &19 for Configurations 3 and 4 respectively. This suggests that most mixing and turbulence generation occur very early, right at the injector face.

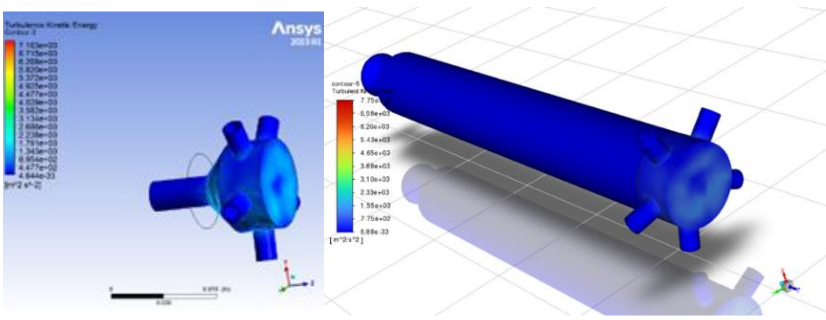

Figure 18: TKE for Configurations 3

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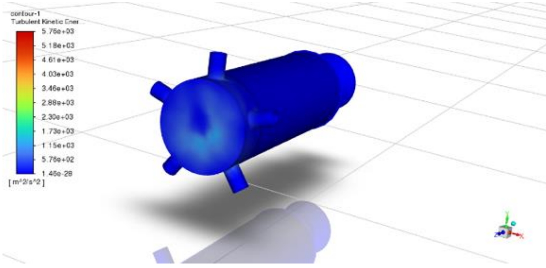

Figure 19: TKE for configuration 4

Conversely, Configurations 5 and 6 exhibit TKE spread throughout the chamber (see Figure 20 and Figure 21). In these cases, turbulence is maintained along the flow path due to the strong recirculation and swirl, with only small TKE remnants at the injector. This pattern indicates a well-mixed flow that remains turbulent through most of the chamber, consistent with the improved mixing performance observed.

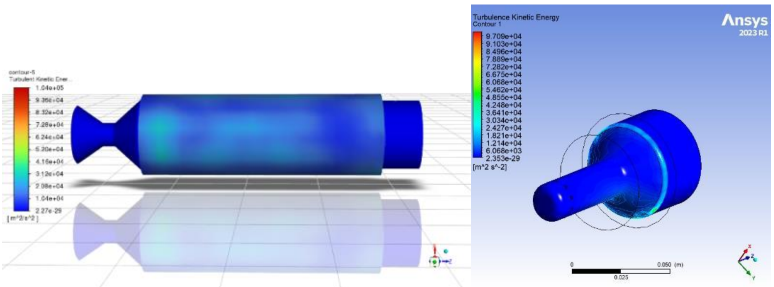

Figure 20: TKE for configuration 4

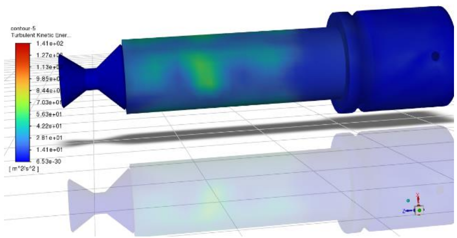

Figure 21: TKE for configuration 6

5. Conclusion

A CFD analysis of the internal ballistics of LOX–HTPB hybrid rockets was conducted, concentrating on injector and chamber design to enhance combustion efficiency. The findings indicate that injector design has a significant influence on oxidiser blending and flow patterns. Swirl-formed injectors (Configurations. 3–4) enhance mixing compared to a basic straight injector (Config. 1), yet the greatest enhancements were achieved using a pintle injector (Config. 5) along with a tangential-entry swirl injector (Config. 6). These later designs resulted in wider oxygen distribution in the chamber, increased chamber pressure, and more consistent turbulence, all of which promote greater combustion efficiency. Specifically, the pintle injector created significant recirculation that postponed combustion downstream (increasing chamber pressure), whereas the tangential swirl produced intense turbulence within the chamber. These results highlight the significance of optimized injector design for LOX–HTPB hybrids. The research indicates that employing sophisticated injector shapes can greatly improve the mixing of oxidizer and fuel, shifting performance closer to the optimal range. Upcoming efforts will broaden this model to incorporate comprehensive solid-fuel regression modeling and will conduct experimental firing tests to confirm the CFD predictions. In general, the findings offer important perspectives for creating more effective LOX–HTPB hybrid engines.

6. References

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7. Conflict of Interest

The author declares no competing conflict of interest.

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