1. Abstract

Hybrid propellant rocket engines have gained considerable attention due to the potential of combining solid and liquid propellants, inheriting both advantages. The ability to control thrust levels and provide throttling over solid-propellant engines, while the simplicity of its design is an advantage over liquid-propellant engines. Thus, providing enhanced safety features and lower cost.

An important part of hybrid rocket research focuses on the characterisation of propellant combustion, due to the peculiar nature of burning propellants in different phases. Part of the engine optimization process, specifically the combustion chamber design, involves iterative adjustments, using rigorous experimental procedures, to the combustion chamber lengths including the grain and the pre and post-chamber. This process is extremely time-consuming. Hence, the current research assesses the impact of the combustion chamber lengths on the overall motor performance through CFD (Computational Fluid Dynamics) simulations and validates results with test firings on a laid-back test engine.

The designed rocket engine comprises a small combustion chamber with axial support from the L-shaped engine mount. The work discusses the initial selection trade study on fuel and oxidizer and details on chamber ignition and purging. The spark ignition method is employed by igniting a fuse that passes into the chamber through the nozzle. Gaseous nitrogen will be used as the purging gas. The engine employs data acquisition systems: thermocouples over the chamber and nozzle, pressure transducers for internal chamber pressure, and load cell for measuring the generated thrust.

The assisting simulation model is built to replicate the manufactured final system and the fluid dynamic assessment for a 2D axisymmetric flow with the assumption of consistent flow across the cross-section of the chamber. The model used will be adaptable to high temperatures and pressure flows, with the effects of chemical combustion reactions satisfied by the K-Omega SST RANS model. The outputs will be in the form of a spectrum across the combustion chamber: pressure, flow velocity, density, vorticity, generated coefficients and thrust. The simulation model is validated through the experimental results, and further research extension to the combustion flow study is proposed based on the coherence of the obtained results.

The obtained experimental results provide information on the thrust levels, temperature gradients, pressure readings and visual plume properties.

A non-linear regression model is generated from the obtained parameters data (from experiments and simulations) to derive an empirical relation between the performance factors and the combustion chamber lengths

1. Literature review

Dequick, B., Lefebvre, M., & Hendrick, P. (2021). **Numerical investigation of the geometrical design of a 1 kN paraffin-fueled hybrid rocket motor**. *Aerospace Science and Technology*, 2021, 1-10. <https://doi.org/10.1016/j.ast.2021.104987>.

This paper presents a numerical investigation of the geometrical design of a 1 kN paraffin-fueled hybrid rocket motor (HRM) at the Université Libre de Bruxelles (ULB). The motor uses liquid nitrous oxide (N2O) as the oxidizer and solid paraffin as the fuel. The study focuses on optimizing performance based on the geometry of the pre-combustion chamber, post-combustion chamber, and nozzle. The following key findings are relevant to your literature review on hybrid engine development, particularly concerning the effects of pre- and post-combustion chamber lengths:

1. \*\*Hybrid Engine Composition\*\*: The ULB-HRM is designed with a paraffin fuel grain and liquid N2O as the oxidizer. A computational fluid dynamics (CFD) model simulates the motor’s performance, incorporating liquid oxidizer spray and entrained fuel droplets.

2. \*\*Numerical Model Overview\*\*: The CFD model includes a two-phase approach to handle liquid oxidizer and fuel droplets. The Reynolds-Averaged Navier-Stokes (RANS) equations with a turbulence model and an Eddy Dissipation Model (EDM) are used for combustion. The model has shown high accuracy in predicting chamber pressure (deviation of +1%) and thrust (deviation of +5%) compared to experimental results.

3. \*\*Pre-Combustion Chamber\*\*: The length of the pre-combustion chamber (L1) was varied by reducing it by 50% and increasing it by 50%. It was observed that increasing L1 initially led to higher chamber pressure and thrust. However, further increases beyond 50% had diminishing returns, with stagnation of chamber pressure (around 25 bar) and thrust (around 1.28 kN). This indicates that extending the pre-combustion chamber beyond a certain length does not improve performance.

4. \*\*Post-Combustion Chamber\*\*: The post-combustion chamber (L2) showed a different behavior. Extending the post-combustion chamber continued to improve performance, particularly increasing chamber pressure and thrust as the reacting species had more time to complete combustion. The extension of the post-combustion chamber proved more effective than the pre-combustion chamber for performance gains, with chamber pressure reaching up to 27.5 bar with longer chambers.

5. \*\*Nozzle Design\*\*: The study also explored the impact of nozzle geometry, including the nozzle length (L3), exit diameter (L4), and half-angle (α). A conical nozzle was used, and the results indicated that while the current design is close to optimal, small improvements in thrust (around 1%) could be achieved by reducing the nozzle exit diameter or increasing the nozzle length.

6. \*\*General Findings\*\*: The study concluded that increasing the post-combustion chamber length leads to the most significant performance improvements, while changes to the pre-combustion chamber length and nozzle geometry have more limited effects. Future work is planned to investigate the design of a minimum-length bell-shaped nozzle for further performance optimization.

This paper provides a detailed parametric analysis of how geometrical changes in hybrid rocket motors affect performance, making it valuable for hybrid engine development focusing on the role of pre- and post-combustion chamber lengths.

Gontijo, M. S., & Filho, R. B. N. (2023). **Design of pre-combustion chambers for hybrid propellant rocket motors and related aspects**. *AIAA SciTech 2023 Forum*. https://doi.org/10.2514/6.2023-2183

This paper presents a detailed study on the design of pre-combustion chambers for hybrid propellant rocket motors (HPRMs), focusing on optimizing chamber length based on a vaporization model and analyzing combustion stability. This research is particularly valuable in hybrid engine development, as it addresses pre-chamber sizing to balance performance, stability, and weight minimization. Here are the key findings relevant to your literature review on hybrid engine performance influenced by pre- and post-combustion chamber lengths:

1. \*\*Hybrid Engine Composition and Importance of Pre-Chamber Design\*\*: The paper highlights that in HPRMs, a liquid oxidizer (e.g., nitrous oxide, N2O) is injected into the combustion chamber to react with a solid fuel. The pre-combustion chamber (pre-chamber) ensures sufficient vaporization of the oxidizer before combustion. If the pre-chamber is too short, combustion instabilities can arise, while excessive length leads to unnecessary weight and heat losses.

2. \*\*Vaporization Model\*\*: The study proposes a vaporization-based algorithm for determining the minimum required length of the pre-combustion chamber to fully vaporize injected oxidizer droplets. This model calculates the chamber length by solving mass and energy conservation equations and considering factors like droplet size, injection velocity, and gas temperature. The model aims to optimize the chamber's length to minimize weight and instability risks while ensuring complete vaporization.

3. \*\*Influence of Pre-Chamber Length on Stability\*\*: A key focus of the paper is the relationship between pre-chamber length (Lpc) and combustion stability. The research shows that short pre-chambers can lead to feed-system coupled instabilities, while longer chambers generally improve stability by allowing complete vaporization. However, excessively long pre-chambers add weight and are inefficient. The study suggests an optimal Lpc/dpc (pre-chamber length to diameter ratio) range of 0.26 to 0.66, offering a balance between performance and stability.

4. \*\*Effect of Droplet Size and Injector Design\*\*: The injector design, specifically the Sauter Mean Diameter (SMD) of the droplets, plays a crucial role in determining the required pre-chamber length. Smaller droplets vaporize faster, allowing for shorter pre-chambers, while larger droplets necessitate longer chambers. The paper emphasizes the importance of injector geometry in optimizing pre-chamber design for hybrid rockets.

5. \*\*Validation with Real Engines\*\*: The paper validates its vaporization model by comparing results with real rocket motors from two test campaigns (SARA and ULBHRE). For some motors, the study found that the pre-chamber length could be reduced without affecting stability, while for others, an increase in length was necessary to prevent instability. This comparison reinforces the model’s reliability in practical applications.

6. \*\*Recommendations for Design\*\*: Based on the analysis, the paper proposes using an Lpc/dpc ratio in the range of 0.26 to 0.66 as a guideline for early-stage design, followed by computational fluid dynamics (CFD) simulations and experimental verification. This approach minimizes instability while ensuring efficient oxidizer vaporization.

7. \*\*Impact on Post-Chamber Design\*\*: While the paper focuses on pre-combustion chambers, it also briefly touches on the potential for future work to extend this vaporization model to post-combustion chambers, as their length similarly affects performance and stability.

This study contributes significantly to hybrid rocket motor development, offering a systematic approach to pre-chamber sizing that balances vaporization efficiency, combustion stability, and weight reduction.