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ECO-THRUST: DESIGNING A LIQUID HYDROGEN ROCKET NOZZLE WITH COMPRESSED AIR VALIDATION FOR SUSTAINABLE PROPULSION

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ABSTRACT

This action research presents the development of a high-efficiency convergent-divergent nozzle designed for a small-scale liquid hydrogen (LH2) rocket engine, contributing to sustainable aerospace propulsion through Technical and Vocational Education and Training (TVET). The project employed a plan-act-observe-reflect cycle to optimize nozzle design, theoretically leveraging the clean combustion characteristics of LH2 to reduce fuel consumption and enhance environmental sustainability. The nozzle was designed using computer-aided design (CAD) tools, applying principles of thermodynamics and fluid dynamics to maximize exhaust velocity for an LH2-based system. For safe and practical validation, static thrust tests were conducted using compressed air as a simulant propellant to assess the nozzle's structural integrity and thrust measurement system. Stainless steel, chosen for its recyclability and mechanical strength, was machined into an integrated nozzle-combustion chamber structure to ensure durability. Tests demonstrated effective thrust generation, with the test cart displacing 0.25 cm in 0.6 seconds at initial thrust and 2.5 cm in 0.2 seconds at peak thrust, validating the design's performance under simulated conditions. Challenges such as pressure spikes due to increased propellant flow and machining imperfections underscored the need for precision fabrication. Reflections highlighted the importance of sustainable manufacturing and safe testing practices in TVET, promoting green engineering. This study enhances practical competencies in design, machining, and performance analysis, reinforcing TVET's role in advancing low-emission propulsion systems for reusable launch vehicles and climate monitoring applications.

1. Introduction

This study develops a nozzle for a liquid fuel rocket engine, a critical component that directs hot gas to produce thrust. The nozzle uses a convergent-divergent design, narrowing at the throat and widening at the exit to accelerate gas. The research applies thermodynamics and fluid mechanics to shape the nozzle for maximum gas speed. The design process considers

steady gas flow, though real flows may include particles that slightly alter behaviour.
Key equations for mass, momentum, energy, and gas properties guide the nozzle's shape to achieve high exit velocity. The design minimizes friction, flow disturbances, and heat loss to maintain efficiency. Stainless steel is chosen for its strength and ease of machining, ensuring a smooth surface. Other materials, like aluminium, are unsuitable due to low heat resistance, unless complex inserts are used.

The nozzle withstands high pressure, heat, and rapid gas flow. Fabricating it as a single unit with the combustion chamber avoids weak joints. Precision machining ensures consistent wall thickness and correct tapering. Bolts securing the assembly must handle strong forces, with a safety factor of two, depending on thread quality and assembly methods. This action research follows a plan-act-observe-reflect cycle to refine technical methods, contributing to TVET through engineering innovation.

2. Literature Review

Liquid fuel rocket engines are used for main or auxiliary propulsion. Recent studies, summarized in Table 1.0, highlight their features. This project focuses on main propulsion engines, which use complex fuel cycles varying in weight, cost, and efficiency. Research shows a trend toward higher combustion pressures, enabling compact designs and better performance (Hagemann & Immich, 2024). Advanced nozzle designs improve gas flow efficiency (Arjun & Kumar, 2020). These advancements inform the current study's design and testing approach.

Table 1. Features of liquid rocket engine types

Purpose	Boost Propulsion	Auxiliary Propulsion
Mission	Propel vehicle along flight path	Minor manoeuvres to adjust flight pad, adjust attitude or orbit maintenance
Applications	Launch vehicle boost and upper stages, large missiles	Spacecraft, satellites, top stages of small missiles, space rendezvous
Total impulse	High	Low
Thrust level	$4500\,\text{N} - 7.9 \times 10^5\,\text{N}$	$0.001\,\text{N} - 4500\,\text{N}$
Feed system	Mostly turbo-pump type; occasionally pressurised feed system for smaller thrusts	Pressurized feed system with high-pressure gas supply
Propellants	Cryogenic and storable liquids	Storable liquids, monopropellants and/or stored cold gas
Chamber pressure	24 bar – 210 bar	14 bar – 21 bar
Cumulative duration of firing	Up to a few minutes	Up to several hours
Shortest firing duration	Typically 5 s – 40 s	0.02 s is typical for small thrusters

3. Methodology

The project began with theoretical research on nozzle design, using thermodynamics and fluid mechanics principles. A convergent-divergent nozzle was designed with CAD software to optimize gas flow. Stainless steel was selected for fabrication. The nozzle and combustion chamber were machined as a single unit to ensure durability. A test stand was built to conduct static tests, measuring thrust with a sensor that converted force to digital signals. Calibration used a weight scale to ensure accuracy. Tests recorded cart displacement to calculate velocity and acceleration. Data were analysed to assess nozzle performance. Observations guided reflections on technical challenges, leading to proposed improvements in machining and sensor calibration.

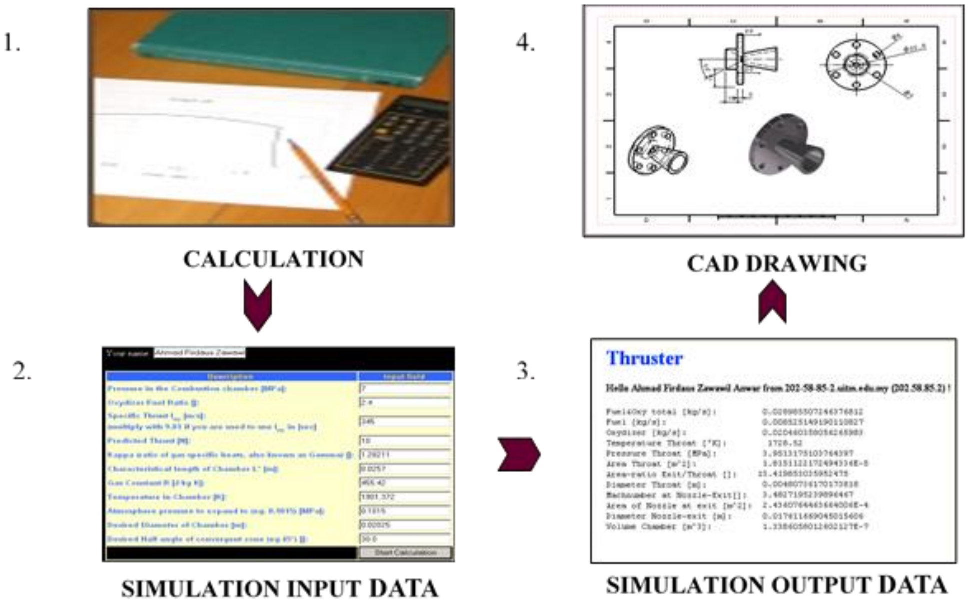

Figure 1. Design Process Steps

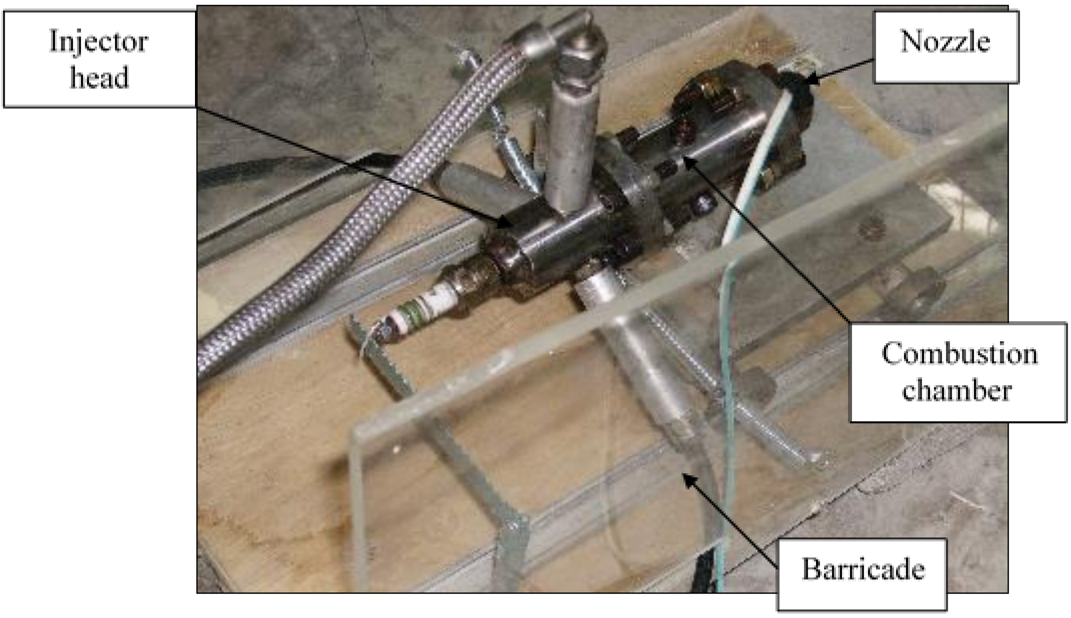

Figure 2. Nozzle and Combustion Chamber Unit

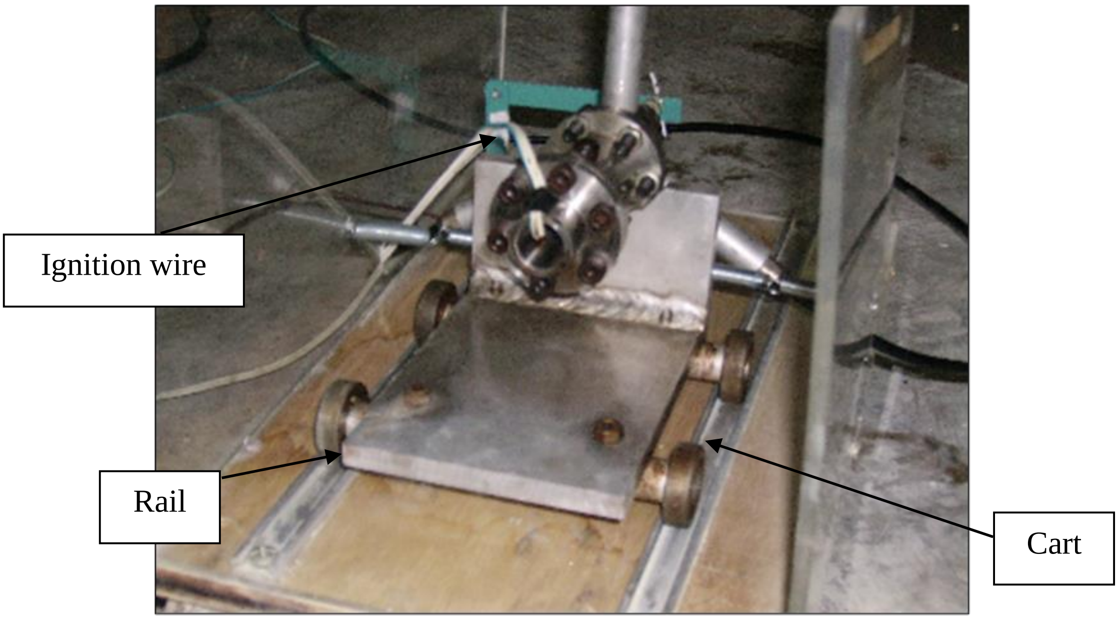

Figure 3. Ignition Setup

4. Discussion

This initiative focuses on static testing, solely involving the engine system without incorporating any aircraft components. The approach to gauging thrust employs a sensor that transforms analog inputs into digital outputs, measured in bits. Consequently, calibration with a traditional weight scale is essential prior to collecting thrust data. Simultaneously, during the force calibration, distance calibration is also conducted. This step is critical for calculating the cart's velocity and acceleration when thrust is generated. Through these calibrations, the accurate thrust force can be reliably determined.

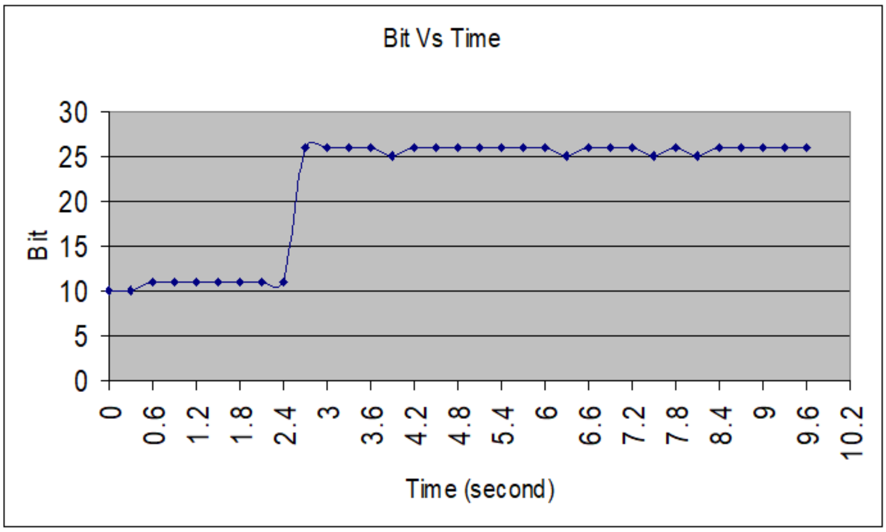

Figure 4. Signal Output Over Time

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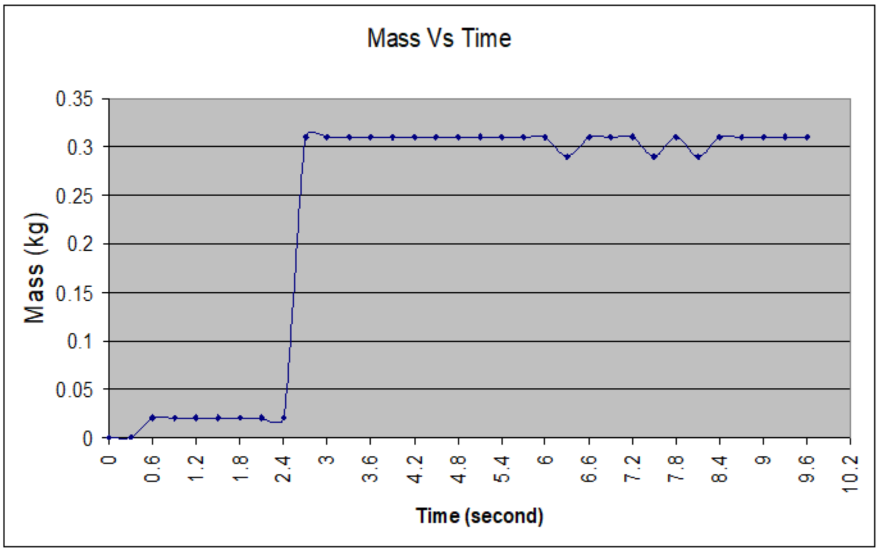

Figure 5. Weight Increase Over Time

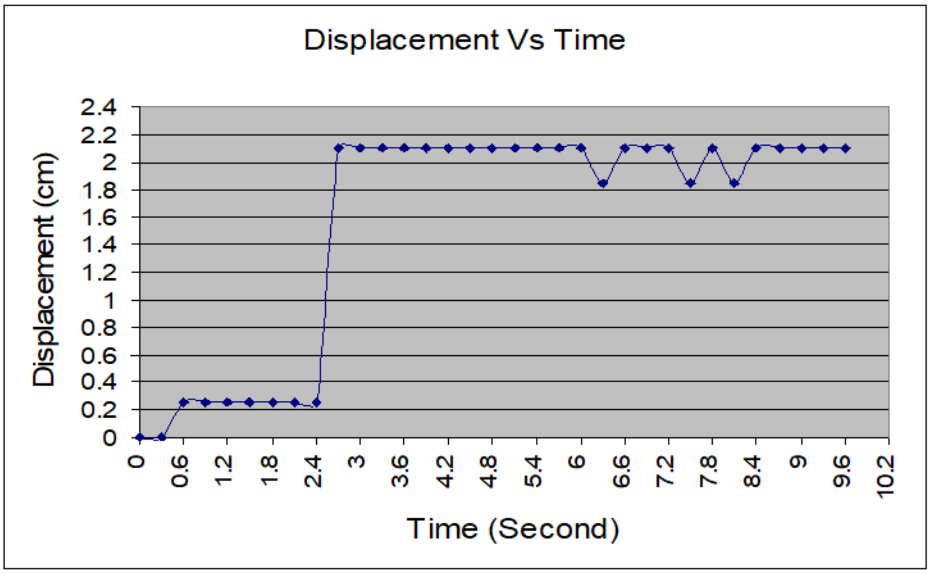

Figure 6. Movement Over Time

By referring to the result (tables and graphs) that is obtained above, it is found that the initial displacement of the thrust device is given in the graph where it is displaced to 0.25 cm from rest condition in 0.6 second. Therefore, the initial velocity is given by;

$$V = \frac{S}{t}$$

$$V = \frac{0.0025\,m}{0.6\,s} \;;\quad V = \underline{\underline{0.0042\, {}^{m}\!/_{s}}}$$

Then it is stopped for about 1.8 second where this condition is considered as no velocity condition. From that condition, it displaced to 2.5 cm in 0.2 second. This condition can be considered as maximum thrust and the velocity at this condition is given by;

$$V = \frac{0.019\,m}{0.2\,s}$$

$$V = \underline{\underline{0.095\,m/s}}$$

So from the velocity that is determined above, the acceleration can be obtained. The acceleration of the thrust device is given by;

$$a = \frac{V-U}{t} \quad ; \quad a = \underline{\underline{0.5\,m/s^2}}$$

The thrust force is the product of mass of the thrust device and its acceleration and is given by;

$$F = ma$$

$$F = (3\,kg)(0.5\,m/s^2)$$

$$F = \underline{\underline{1.5\,N}}$$

The combustor's thrust hinges on the speed and volume of hot gas expelled through the nozzle. As the total propellant quantity rises, the propellant reaction intensifies, generating greater heat and pressure. Heat and pressure within the combustion chamber influence the overall mass flow rate at the nozzle. Theoretically, the mass flow rate at the nozzle produces the combustor's net thrust. Results indicate that propellant velocity is directly proportional to the flow rate, and as noted, the propellant reaction also correlates with this flow rate. An enhanced chemical reaction increases the volume of hot exhaust passing through the nozzle. The exit velocity, shaped by the rocket nozzle's design, reaches supersonic levels.

5. Conclusion

This system is equivalent to the theoretical design where the thrust developed is equal to total mass flow rate of the propellant multiply by exit velocity. This can be proved by applying the following relation;

$$F = \dot{m} \times V_e$$

Increased propellant flow enhances thrust through higher pressure. The nozzle’s shape controls gas velocity, with the throat limiting flow due to choking. The study refines technical expertise, offering insights for TVET research practices.

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