Bluff Body Induced Regression Rate Enhancement in Hybrid Motor

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1 Introduction

Hybrid rocket propulsion combines the simplicity of solid fuels and the flexibility of liquid oxidizers, offering safer operation and reduced system complexity compared to traditional propulsion systems [1]. However, their major drawback is the low regression rate of fuel, which limits performance. Researchers have addressed this issue through three approaches: optimizing fuel properties (e.g., paraffin blends, metallic additives), employing advanced injection and grain design techniques (e.g., swirl injection, radial flow) [2, 3]. This study focus on bluff bodies by placing geometric obstructions in the combustion chamber to improve turbulence, improve fuel-oxidizer mixing, and stabilize the flame, thus increasing the regression rate [2, 4].Three shapes of bluff body; conical, cuboid and hemispherical has been tested in the study. A fuel mixture of 30% microcrystalline wax and 70% paraffin wax was used due to its low cost and manufacturability despite weak mechanical properties [4,5]. Oxygen gas served as the oxidizer, and experiments were conducted with a single-port grain configuration on a custom-built thrust bed test setup at IIT Bombay.

2 Methodology

Wax-based propellants theoretically offer regression rates 3–5 times higher than conventional solid fuels [6]; however, experimental results indicate a lower rate of around 2.48 mm/s [7]. The fuel used is fabricated in a single port grain configuration for simplicity and reduced preparation time. The grains were produced using the melt-and-cast method described by Dinesh and Kumar (2024) [8], in which the melted wax was poured into the mould with a mandrel coated with silica grease. To minimize shrinkage and defects, cooling was controlled in a hot air oven starting at 60°C and reduced by 5°C per hour; additional wax was added during cooling to maintain grain length. After being cooled to 45 ° C, the grains were air dried to room temperature and extracted. Further, computational studies were performed to determine the dimensions of the most efficient bluff bodies. The hemispherical design (9.5 mm radius with 2.5 mm step) creates uniform recirculation, the conical design (6 mm length, 19 mm diameter) generates sharp turbulent flows, and the cuboid design (9.5 mm side) induces strong shear layers and larger recirculation zones. These bluff bodies were mounted on the head end using M2.5 threaded fittings. The hybrid rocket motor comprised an SS 304 combustion chamber, showerhead injector, and a graphite convergent–divergent nozzle, with oxidizer flow (63 g/s) regulated by a solenoid valve and sequential timer. Regression rates were determined using the weight-loss method by measuring grain mass before and after firing. Oxidizer mass flux was calculated using the port area and oxidizer flow rate, and (1) was established from the test data.

$$\dot{r} = a\left(G_{\text{ox}}\right)^{n} \tag{1}$$

where, r is the regression rate in mm/s, a is the mass flux constant, G_{ox} is the mass flux in gm/s and n is the mass flux exponent.

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3 Results and Discussion

The experimental results show that the conical bluff body provides the highest regression rate of 5.3 mm/sec, closely followed by the hemispherical body with a regression rate of 4.68 mm/sec. From the computational results obtained using ANSYS, it was observed that both shapes promote strong flow disturbances and create an efficient mixing environment, directly enhancing combustion. However, the cuboid bluff body exhibited a significantly lower regression rate of 3.05 mm/sec. The baseline case, without any bluff body, had the lowest regression rate of 2.28 mm/sec, indicating that the introduction of bluff bodies significantly improves the performance of the fuel. The conical and hemispherical bluff bodies exhibit higher regression rates near the head end, which gradually stabilize along the port length as their influence diminishes. A slight increase in regression rate near the nozzle end is observed, attributed to erosive burning from boundary layer turbulence.

4 Conclusion

From the experimental evaluation of bluff body geometries in hybrid rocket motors, it is evident that geometry plays a crucial role in enhancing the fuel regression rate. Among the tested configurations, the conical bluff body delivered the highest performance, achieving a regression rate of 5.3 mm/s which is 2.3 times greater than the baseline without a bluff body, followed by the hemispherical shape at 4.68 mm/s (about twice the baseline) and the cuboid at 3.05 mm/s (1.3 times the baseline). The influence of bluff bodies was most pronounced near their location, with regression rates decreasing along the axial length of the fuel port due to the limited span of turbulence and flow disturbance. Overall, the results highlight the effectiveness of conical and hemispherical bluff bodies in improving combustion efficiency and fuel regression rates in hybrid rocket motors.

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