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IMPULSE AND CHAMBER PRESSURE IN HYBRID ROCKETS

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INTRODUCTION

Hybrid rockets—rockets that use a liquid oxidizer and solid fuel cylindrical grains—are currently experiencing a resurgence in research rocketry due to their comparative safety benefit.[1] The unique design of a hybrid rocket enables fuel and oxidizer input regulation, and thus modulation of the combustion chamber pressure.[2] This reduces the risk of explosion.[3] This paper will give a basic overview of the function of a hybrid rocket, the role of injector plate geometry and rocket fuel on thrust, and the results of the Rice Eclipse research team on studying the effect of injector plate geometries and rocket fuel combinations on thrust and impulse. The purpose of this research is to discover a fuel grain and injector plate combination with the thrust necessary to launch a hybrid rocket into suborbital space.

SOLID ROCKETS

Most entry-level, low-hazard rockets use solid motors.[4] Solid rockets are generally considered to be the safest option because of the consistent burn profile.[5] These rockets have a solid cylinder of fuel in their combustion chamber that contains a blend of rocket fuel and oxidizer.[5] Through the course of flight, the fuel/oxidizer blend gradually depletes like a high power candle until the rocket reaches its apogee.[5] Since the fuel and oxidizer are initially mixed together, it is highly unlikely for a solid rocket to have a concentration of fuel necessary for instantaneous combustion, which would result in an explosion.[5]

LIQUID ROCKETS

Typical rockets that are deployed in space are liquid rockets.[6] These rockets contain tanks of liquid oxidizer and liquid fuel that are atomized in the combustion chamber to burn at the high efficiencies required to achieve the impulse necessary for escape velocity.[7] Particularly, the atomization provides the high surface area-volume ratio that is necessary for an efficient burn and allows the rocket to have the extremely high thrust. The disadvantage of liquid rockets is the huge safety risk they pose.[7] Having a liquid combustion system makes the oxidizer and fuel dangerously close to blending, which can create a concentration of oxidizer-fuel mixture susceptible to a spark and resultant explosion.

HYBRID ROCKETS

Hybrid rockets combine the best of both solid and liquid rockets.[6] The liquid oxidizer of the hybrid rocket is atomized over the solid fuel to give a high-thrust yet controlled burn in the combustion chamber.[2] Although the sophistication of hybrid rocket engineering prevents most novice rocket builders from constructing hybrids, Rice Eclipse has constructed the fifth amateur hybrid rocket in America—which we call the MK1.

INJECTOR PLATES

Injector plates are metallic structures that function like spray guns and divide the stream of oxidizer into thousands of small atomized parts.[8] A variety of designs or geometries exist that serve to break up oxidizer flow; the designs we considered in this study are the showerhead and impinging designs.

SHOWERHEADS

Showerhead injectors function similarly to household showerheads.[4] A series of radially placed holes taper inwards as they move through the injector plate, confining the oxidizer fluid to a very small space before releasing it as a spray in the combustion chamber.[8] The fluid atomizes because the oxidizer accelerates as it travels through the constrained small holes but suddenly decelerates as it reaches into the combustion chamber due to the rapid change in pressure.[8] This process of breaking up liquid streams due to sudden resistance to flow is called the venturi effect.[8]

IMPINGING PLATES

The second type of injector plate studied is an impinging injector plate4. In this style of injector plate, the holes of the plate are placed facing one another.[9] As the oxidizer flows through the holes of the plate, the streams impinge, or collide at a central location.[9] Upon collision, the streams atomize.[4]

It is hypothesized that this plate structure should result in much better performance because of greater atomization compared to a corresponding showerhead plate.[4] For this project, the angle of the impinging holes was chosen to be 30 degrees from the normal in order to optimize impingement and atomization at the end of the pre-combustion chamber.[9]

FUEL GRAINS

Rocket fuels are often made of various materials that complement each other's chemical properties to produce a high efficiency burn.[10] These fuel components are held together in a cylindrical grain through the use of a binder compound that is also consumed in combustion[11] Therefore, it is important for both the standard fuel components and the binder to burn efficiently.11 The efficiency of a burn is quantified in the fuel regression rate, which is how fast the fuel grain is depleted.[12] While this rate varies based on combustibility and other chemical properties, it also heavily depends on the surface area available for burning.[12] Fuels with high surface area, like those in a liquid or gaseous state, can achieve high regression rates.[12] Thus, hybrid and solid rocket enthusiasts have been attempting to develop high surface area grains for efficient burns; this is has been previously achieved by using exotic grain configurations designed to maximize the exposure of the grain.[12] Rice Eclipse has taken the different approach by using a standard cylindrical fuel grain that incorporate high regression rate liquefying paraffin with conventional solid rocket fuel. These fuel grains were combusted with a nitrous oxide oxidizer.

PARAFFIN FUEL

Hydroxyl-terminated polybutadiene (HTPB), is the most commonly used rocket fuel for both hybrid and solid rocket motors.[13] In solid rockets, the physical properties of HTPB make it an ideal chemical to both bind the oxidizer into a strong yet elastic fuel grain and serve as source of fuel.[12] However, HTPB does not burn with efficiencies required to accelerate rockets into orbital velocities.[14] To improve pure HTPB grains, researchers have experimented with the addition of paraffin, a waxy compound that burns with a higher regression rate than HTPB, in the fuel grain.[15] Under the high temperatures of the combustion chamber, solid paraffin wax forms a thin layer of low surface tension liquid on the face of the fuel grain cylinder that is exposed to the oxidizer.[16] The layer of liquid vaporizes due to the high flow rate and pressure of the oxidizer, producing the large surface-area-to-volume ratio that is common in solid and liquid rockets.[16] This liquefaction phenomena allows paraffin to produce high regression rate fuels in both hybrid and solid motors.[16] However, paraffin by itself cannot be molded into a fuel grain due to its low viscosity.[16] Thus, the inclusion of HTPB enables the production of a moldable fuel grain that possesses the high regression rate of paraffin wax.[17]

MATERIALS AND METHODS

These tests were conducted in Houston, Texas in the MK1 test motor. The maximum combustion chamber pressure of MK1 was set to 500 psi. The motor used a load cell for thrust measurements and an internal pressure sensor for the combustion chamber profile. Each test fire lasted for four seconds, and three fires were conducted per configuration to ensure reproducibility and consistency of data.

We tested two types of fuel grains with HTPB and paraffin grains at 0% paraffin/100% HTPB and 50% paraffin/50% HTPB. All of these tests utilized a nitrous oxide oxidizer. Each of these grain types were cast in the Rice University, Oshman Engineering Design Kitchen.

The injector plates were made out of stock steel and were machined in the Rice University, Oshman Engineering Design Kitchen. The values used to drive the design of the injector plate are the desired mass flow rate of the oxidizer: 0.126 kg/s and the desired pressure drop across the injector plate: 1.72 MPa.

Graphite nozzles with an entrance diameter of 1.52 in, a throat diameter of 0.295 in, and an exit diameter of 0.65 in were used. Each nozzle is 1.75 in long and has a converging half angle of 40 degrees and a diverging half angle of 12 degrees.

RESULTS

Three different fuel and injector plate combinations were studied. We performed a base case test of 0% paraffin/100% HTPB in a shower head plate. We then studied the effect of adding an impinging plate to the 0% paraffin/100% HTPB grain and went on to test a 50% paraffin/50% HTPB on the shower head palate. The reason we tested these configurations is to see how having a paraffin blended fuel grain and adding an impinging plate independently affected our rocket performance. The three scatter plots below show the thrust from each of the grains during a test fire. Thrust has a directly proportional relationship to the specific impulse of the rocket.

DISCUSSION

50% PARAFFIN TEST

The 50% paraffin grain showed a significant improvement compared to the 0% paraffin base case, increasing the average thrust by 58% from 380 lbf to about 600 lbf. The paraffin fuel grain also improved the consistency of the burn due to the even spread of the paraffin grains in the fuel. Although chamber pressure did increase from about 23 psi to

38 psi, this increase in pressure is well below the 50 psi operating capacity of the rocket and would not be a handicap for the fuel grain.

IMPINGING PLATE

The third test fire, which demonstrated the impinging plate, maintained an average thrust of 700 lbf at maximum capacity—the highest average thrust. This is because the impinging injector plate increases the atomization of the oxidizer and the surface area available for combustion, intensifying the resulting burn. This increase in burn efficiency also reduces the overall burn time of the fuel and in this case shortened the fire to about two seconds from a four second burn in the base case.

CONCLUSIONS

The data show that the impinging injector was successful at achieving higher thrust burn. The paraffin fuels also demonstrated improved performance from the traditional HTBP fuel grains. This improvement in performance likely results from the reduced energy barrier to vaporization in the paraffin fuels compared to HTPB. The combination of improved vaporization and atomization allowed the impinging injector plate test results to show significantly better maximum thrust than all other tested plate combinations. Future testing can focus on combining the impinging plate with different concentrations of paraffin to take full advantage of increased atomization and surface area.

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