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Hybrid Rocket Engine Design Utilizing a Polymer Matrix Encapsulating Pulverized Fuel

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This study involved the use of a powder-filled, ABS matrix fuel grain as a means to overcome the low fuel regression rates and limited thrust typical of polymer-based hybrid rockets. Appropriately chosen powdered fuels do not melt or clump and consequently provide a high surface area and rapid combustion when the individual polymer cells rupture and discharge their contents into the combustion chamber. Previous experimental work has validated this concept, revealing faster combustion and higher total impulse values than those achieved using conventional, solid polymer grains. Because the initial studies served primarily as a proof of concept, their limited scope did not answer many questions regarding motor performance. The current paper describes the design and testing of an improved polymer matrix that allows more accurate characterization of motor performance, including the parameters of specific impulse and characteristic velocity, and presents results of testing at higher combustion pressures. The current design process focuses on optimizing the oxidizer to fuel ratio and accounting for and minimizing any powdered fuel losses previously observed.

I. Introduction

Hybrid rocket engines share some of the advantages of both solid and liquid propulsion. Specifically, they are substantially less complex than liquid bipropellant designs, since there is only one fluid handling system. They also are safer and less prone to explosion than solid motors and can be throttled, stopped and restarted like a liquid engine. The propellants typically are non-toxic and don't require the extreme safety precautions of many other propulsion designs.

However, hybrids often have a fairly low thrust, which depends on the fuel burn rate. Numerous schemes have been developed to enhance the regression rate and improve thrust, including the use of multi-port combustion, vortex injection of the oxidizer, and the addition of metal and oxidizer particulates to the fuel grain [1-3]. Each of these approaches, however, has associated drawbacks, and, with notable exceptions, hybrids have not yet come into widespread use. Moreover, due to the increasing surface area of the fuel during a burn, oxygen to fuel ratios typically shift over the course of the burn and do not remain optimal.

Three-dimensional printing has recently allowed the fabrication of complex geometries for rocket engines which would be impractical to machine [4-6]. These same features of 3-D printing may prove useful in addressing the issue of low regression rates, limited thrust and varying O:F ratio. Moreover, recent developments in the use of 3-D printed ABS for cryogenic applications [7] indicate that a printed fuel grain might be of use for propulsion in very cold environments such as during a Mars landing or ascent.

II. Background and Preliminary Work

Inspired by the well-known phenomena of coal and grain dust explosions [8], our group has developed and tested a 3-D printed, ABS (acrylonitrile butadiene styrene) matrix, containing powdered fuel in the voids (Figure 1), Ref 9. The configuration incorporated a single combustion port. When the individual cells burned through, the powdered fuel was released into the combustion chamber, providing a high surface area for burning and leading to

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both a higher regression rate and greater thrust than that produced by a solid polymer grain. This design requires the use of a powdered fuel that does not melt or clump prior to burning. Thus, polymers are not appropriate for use in the cells, but metal flakes, powdered graphite, pulverized coal, petroleum coke and other materials hold promise.

The potential of coal as an aerospace propellant is not a new idea. In fact, Hermann Oberth and others attempted to use both coal and graphite as fuels in early rocketry experiments but met with little success, largely because of the materials' high effective heats of vaporization [10]. In other efforts, Alexander Lippisch designed a ramjet burning granulated coal to power the P13A for the Luftwaffe during the Second World War. It is not clear if the plane was ever built, although a glider version was flight tested [11]. More recently, the possibility of using pulverized coal was briefly mentioned in a NASA report [12] and outlined in more detail in Ref. 13, where the results of combustion and regression rate testing are described. However, this work involved the use of a traditional, HTPB binder rather than a porous matrix, and the results were hindered by the formation of a surface char consisting of a mixture of HTPB and liquified coal. The authors felt that the char layer impeded the entrainment of coal particulates in the gas flow and degraded performance. This problem might be overcome by having the coal particulates discharge en masse into the flow from pockets in a printed matrix rather than being individually embedded in a binder.

Fig. 1 Polymer matrix fuel grain. The one-inch diameter, single combustion port is in the center. Powdered, non-melting fuel is placed in the void spaces.

A. Grain Design and Fabrication

The grain design was developed in SolidWorks, and a stress/strain/displacement analysis was carried out to ensure that the cells did not prematurely rupture from the high pressure in the combustion chamber. This was performed assuming combustion pressures of 300, 500, and 1000 psia. Cell wall thicknesses were adjusted to maximize the powdered propellant volume, while maintaining structural integrity of the matrix. The CAD model was used to print the matrix in ABS at a layer thickness of 0.013 inches on a Fortus 250 MC FDM 3-D Printer at the University of Tennessee Knoxville. The grain was 25.4 cm in length by 6.2 cm in diameter, with a central port 2.54 cm in diameter. Approximately 50% of the matrix volume was void space, and 50% was ABS. The grain dimensions were chosen to be easily compatible with the existing thrust stand at the UT Knoxville Rocket Test Facility (described in the Appendix and in Reference 14). The void spaces ran the length of the grain to allow the powdered fuel materials to be packed into the matrix easily. Pulverized coal was obtained from the Tennessee Valley Authority in Knoxville. For other tests, commercially-sourced, powdered graphite was employed (General's Powdered Graphite). Petroleum coke was generously provided by the Oxbow Corporation and ground in house by our team members, producing a relatively non-uniform grain size.

B. Thrust Stand Testing

Multiple live-fire tests were carried out, each under identical conditions except for the type of fuel. In each case, gaseous oxygen was used, regulated to a supply pressure of 800 psig and injected axially at the upstream end of the grain. Ignition was accomplished by means of three bundled commercial fireworks sparklers, lit using a 10 ohm, 1/4 watt electrical resistor. All fuel grains had the same initial dimensions given previously for the printed matrix. The nozzle had a throat diameter of 0.5 inches and an area ratio of approximately 3.06. Run times were 4.6 seconds. Combustion pressures in these preliminary tests were very low and depended on the fuel in use, ranging from approximately 0.4 MPa to 0.7 MPa. Combustion pressure was not deliberately controlled but was a function of the fuel burn rate, coupled with the oxygen flow rate and throat diameter, with the latter two parameters consistent from run to run. Experimentally measured parameters included thrust, combustion chamber pressure, oxygen and fuel consumption, and oxygen supply pressure. Thrust was sampled at a rate of 100 HZ and smoothed using a 9-point running average.

Test results are summarized in Table 1. Oxygen consumption was reasonably consistent, with an average of 261.3 gms and a standard deviation of 7.7 gms or 2.95%. Based on the initial port diameter, this gives an average oxygen flux of 11.2 gm/cm2/s. Some of the variation between runs is likely due to differences in the mass of oxygen supplied. This is supported by the two polypropylene data sets, where the case with a higher mass of supplied oxygen has a nearly proportional increase in total impulse. However, despite this minor inconsistency in the supplied oxygen mass, the trends are clear, and, overall, the printed matrix grains produced significantly higher total impulse than any of the commercially-sourced, polymer grains.

Thrust vs time profiles are shown in Figure 2 for selected cases, focusing on ABS, printed ABS and matrix grains. The printed, solid ABS offered a modest improvement over the commercially-sourced material, while the matrices increased the total impulse from 17 to 45 percent. Unexpectedly, the empty matrix provided the best ISP and total impulse, although its low density would almost certainly make its use impractical. While the reason for the relatively weak performance of the coal/graphite mixture is unclear, video records seemed to indicate that in the case of the graphite/aluminum mixture, the aluminum may have melted and clumped, leading to incomplete combustion. The petcoke powder was not as fine as the graphite or coal and likely had a lower combustion efficiency, yielding a lower total impulse.

Unfortunately, in all of these preliminary matrix tests, a significant amount of unburned, powdered fuel was ejected from the motor as the oxygen was cutting off, making an accurate determination of the mass of fuel consumed, O:F ratio, specific impulse and C* impossible. Similarly, kerosene ran out of the engine after the burn was completed, so an accurate mass determination was not possible in that case either. These uncertain results are indicated in Table 1 by question marks adjacent to the relevant numbers. Therefore, for these cases, the indicated specific impulse values represent a lower limit for the actual value achieved. This problem would not, however, be an issue if the fuel grain were allowed to burn completely, as would be expected in a flight vehicle. In many cases the O:F ratio seems to be significantly lower than ideal. However, in the case of the powdered fuels, it is not entirely clear, since the fuel mass is not known with any precision.

Table 1. Preliminary Hybrid Propellant Testing Results

FUEL TYPE	Oxygen Consumed, gms	Fuel Consumed, gms	Specific Impulse, s	Total Impulse, N-sec
Empty, 3D Printed ABS Matrix	258	131	196	748
3D Printed Matrix with Graphite	266	230 ?	146 ?	709
3D Printed Matrix with Coal	266	156 ?	169 ?	700
Kerosene-saturated polypropylene filter	257	218 ?	149 ?	696
Paraffin	256	208	147	667
3D Printed Matrix with 50-50 Graphite/Aluminum Mix	252	184 ?	149 ?	636
3D Printed Matrix with 50-50 Coal/Graphite Mix	252	153 ?	157 ?	623
3D Printed Matrix with Petcoke	265	135 ?	154 ?	603
3D Printed, Solid ABS	264	66	178	575
Commercial ABS	263	56	165	515
Polypropylene	280	29	144	436
Polypropylene	264	34	138	403
Plexiglass	254	37	137	391

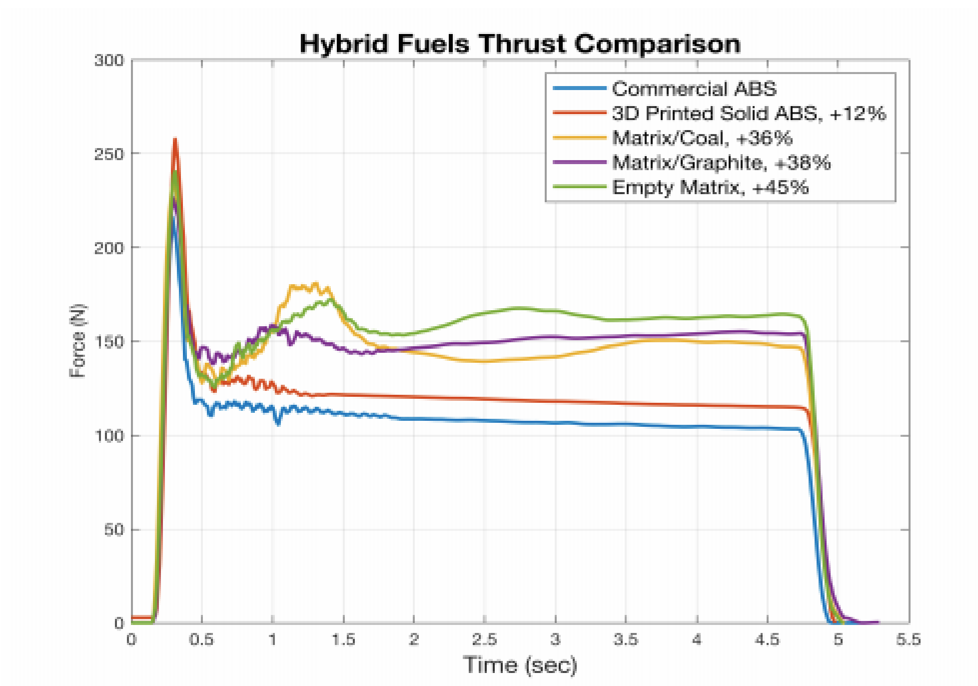

Fig. 2 Preliminary thrust - time profiles for selected fuel grains. All conditions are the same in each test, except for the fuel type. The percentage values indicate improvement in total impulse above that for the commercially-sourced, solid ABS grain.

III. Current Effort

The results of the previous work validate the concept, showing that powdered fuels encased in a 3-D printed, ABS matrix can provide significantly higher thrust and total impulse than traditional polymeric fuels under identical conditions. While encouraging, these preliminary results leave many questions unanswered, including the following:

1) What are the actual, achieved values for specific impulse and C* for the various matrix-based fuels?

2) What effect would higher combustion pressures have on the relative performance of the various fuels tested? Would the advantages of the pulverized fuels be maintained?

3) Can the experimental O:F ratio be used effectively to adjust the grain length and achieve improved performance?

4) Could satisfactory performance be achieved using a powder-filled matrix with a more flight friendly oxidizer such as nitrous oxide?

5) Could a catalyst be used in a motor employing nitrous oxide as the oxidizer to decrease the activation energy of the nitrous decomposition and thereby speed reaction rates and improve combustion efficiency? If so, what is the best approach to implement the catalyst? Significant work has previously been done on this topic at the University of Surrey, but difficulties were encountered with high temperature degradation of the catalyst materials [14].

6) What is the ideal design for an enclosing matrix? Are less expensive alternatives available to be used in lieu of the 3-D printed matrix tested in this study?

7) Would the addition of a post combustion chamber just upstream of the nozzle improve performance?

8) What is the optimal method to achieve proper mixing of the powdered fuel and oxygen?

A. Modified Polymer Matrix

To address the first of these questions, the matrix shown in Figure 3 was designed. This configuration allows all of the powdered fuel to be consumed prior to engine cutoff, without a risk of exposing the walls of the pressure vessel to hot combustion products. As a result, a more accurate determination can be made of the mass of fuel consumed, thereby permitting a true assessment of ISP, C* and O:F ratio.

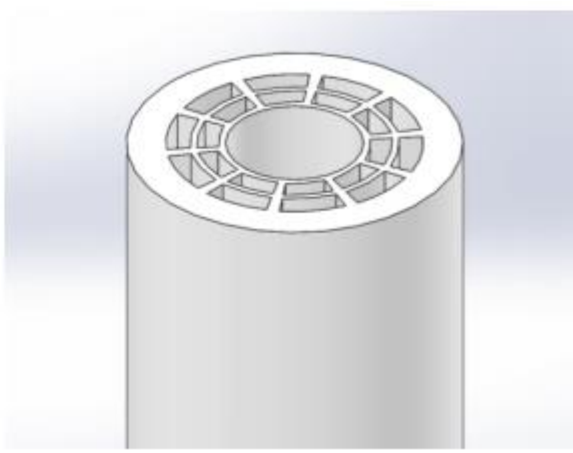

Fig. 3 ABS matrix designed to consume all the powdered fuel and allow a more accurate determination of C*, O:F ratio, and specific impulse.

Testing was carried out using this matrix filled with powdered graphite. The burn duration was 4.6 seconds, the gaseous oxygen was regulated to a supply pressure of 1000 psi and injected not axially but with a vortex head-end, vortex injector. The oxidizer flow pattern can be appreciated in Figure 4, taken during motor shutdown using a

Plexiglas grain. The nozzle throat diameter was 1.02 cm. Experimental results for the modified polymer grain with graphite infill are shown in Table 2.

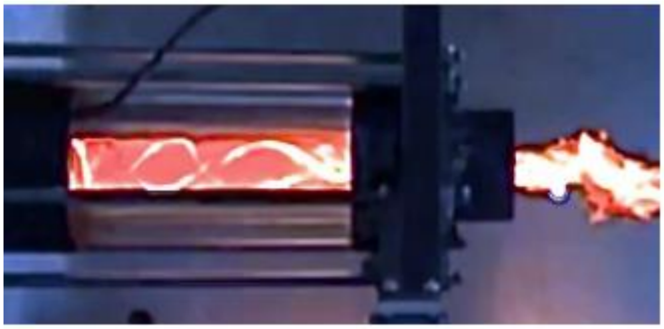

Fig. 4 Vortex flow pattern from head end injection of gaseous oxygen.

Table 2. Modified polymer matrix with graphite infill

Oxidizer Mass Consumed	265 gms
Fuel Mass Consumed	249.5 gms
O:F Ratio	1.06
Total Impulse	835 N-s
Specific Impulse	165 s
C*	1295 m/s

These results indicate that the low O:F ratios found in the preliminary testing (Table 1) were not due entirely to the loss of unburned, powdered fuel at engine shutdown. This seems to imply that virtually all of the oxidizer is consumed in the upstream portion of the combustion chamber, and fuel from the downstream portion is eroded from the walls but does not react. As a result, a shorter fuel grain (60% of the previous length) has been fabricated.

Initial testing of the shorter fuel grain showed much improvement in the O:F ratio following an identical burn time of 4.6 seconds, vortex-injected oxygen at a supply pressure of 1000 psi, and nozzle as in the previous full-length fuel grain test. Results for this polymer grain with graphite infill are shown in Table 3.

Table 3. Modified polymer matrix (60% length) with graphite infill

Oxidizer Mass Consumed	279 gms
Fuel Mass Consumed	131.5 gms
O:F Ratio	2.12
Total Impulse	684 N-s
Specific Impulse	170 s
C*	1417 m/s

While these results do show an improvement over the low O:F ratio of the original fuel grain, the shortened matrix overshot the optimal O:F ratio of approximately 1.75. This optimized value was determined by analysis of gaseous oxygen and ABS propellant with the heat of formation for ABS assumed to be 1097.4 kJ/kg [15]. Design and fabrication of a slightly increased fuel grain length (approximately 70% of the original length) is currently underway and will be tested in the near future as well as the addition of minor, varying percentages of powdered aluminum to the graphite infill.

B. Future Development

Once these preliminary studies are completed, testing will be conducted with alternate matrix materials (injection moulded plastic, wax honeycomb, plastic honeycomb, etc). Furthermore, variation in the mixture of the powdered components implemented radially from the combustion port will be used (either with or without modulation of the oxidizer flow rate) to tailor the thrust profile to the specific needs of a potential mission. The use of such heterogeneous fuel blends will also be examined as a means to overcome another issue typical of hybrids, the shift in the O:F ratio over the course of a single burn.

Appendix

Background and Test Facilities

The University of Tennessee Knoxville has carried out hybrid rocket research since 1999. The on- campus test facility includes a covered concrete pad and steel frame thrust stand, storage facility, a sand-filled blast wall, pressure and force instrumentation, video monitoring equipment, solar power, and buried data and video feed cables leading to an 18,000 lb concrete bunker. This facility has been used for several NASA- sponsored projects and has handled a range of propellants including liquid and gaseous oxygen, nitrous oxide, paraffin, kerosene, beeswax, ABS, PMMA, polypropylene, etc.

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