Work In Progress: This is Rocket Science: Development and Testing of a Hybrid Rocket Motor in a Rocket Propulsion Course

Anthony J. Marchese
Rowan University, Department of Mechanical Engineering,
Glassboro, NJ 08033 marchese@rowan.edu
http://users.rowan.edu/~marchese

Abstract **- This paper describes a unique design and laboratory experience that was incorporated into an introductory rocket propulsion course. Specifically, each student team designed, built and tested a 7 lb_f thrust hybrid rocket motor. The thrust chambers were fabricated from aluminum and the nozzles were fabricated from graphite. Solid fuel grains consisting of HTPB and HTPB/Al were produced by each team. Each rocket was tested on a thrust stand that enabled the measurement of instantaneous oxygen mass flow rate, chamber pressure (P_c) and thrust. With these data, each team was able to measure specific impulse (I_{sp}), characteristic exhaust velocity (C*) and thrust coefficient (C_F) and compare these measurements to their theoretical models, which predicted instantaneous O/F, C*, P_c, and thrust. This design experience, which can be easily and inexpensively replicated at other institutions, was universally evaluated by students as a major highlight in their education to date and multiple students have expressed an interest in a career in aerospace engineering as a result.**

Index Terms – Rocket Propulsion, Design, Laboratory Experiments.

INTRODUCTION

One of the primary obstacles that has prevented human exploration of Mars in the 35 years since the moon landing is the propulsion system requirements. Given NASA's new initiative to refocus its efforts on human exploration of the moon and Mars, it is imperative that a new generation of rocket propulsion experts be produced to make NASA's goal a reality. The timing for this endeavor is particularly critical since many of the early pioneers in rocket propulsion have retired or passed on. A typical course in Rocket Propulsion is primarily lecture driven, which can be effective for students already interested in rockets. However, since today's undergraduate student has not had the benefit of growing up in an era when every child wanted to be an astronaut, a hands-on experience is particularly significant to provide students with practical experience.

This paper describes a unique design and laboratory experience that was incorporated into an introductory rocket propulsion course at Rowan University in Fall 2005. Specifically, each student team designed, built and tested a 7 lb_f thrust hybrid rocket motor. Each rocket was tested on a thrust stand that enabled the measurement of instantaneous oxygen mass flow rate, chamber pressure (P_c) and thrust.

HYBRID ROCKET MOTOR DESIGN AND FABRICATION

The goal of the semester design project for the Rocket Propulsion course was for each student team to design, build and test a hybrid rocket motor and to compare the measured performance with theoretical calculations. The constraints for the design project were as follows:

- Oxidizer must be gaseous oxygen (GOX)
- Maximum Chamber Pressure: 115 psia
- Maximum GOX flow rate: 500 SLPM
- Minimum initial thrust: 5 lb_f
- Fuel grain outer diameter = 1.175 in
- Maximum Fuel Grain Length = 12 in

The choice of the solid fuel was not constrained. However, students needed to choose a fuel for which thermodynamic and regression rate data were available. The latter requirement resulted in each team choosing either hydroxyl-terminated polybutadiene (HTPB) or HTPB mixed with powered aluminum.

Using the NASA CEA Chemical Equilibrium computer code, each team calculated chamber temperature (T_c), ratio of specific heats (γ), average molecular weight (MW), characteristic exhaust velocity (C*) and all equilibrium mole fractions of all of the exhaust products as a function of oxidizer to fuel ratio (O/F). The teams then developed a detailed analytical model of the hybrid rocket motor and used it to iteratively optimize their final design. Using their analytical model, the students were able to determine fuel grain length, port diameter, throat diameter, nozzle area ratio, nozzle exit diameter and calculate the variation in flow rate, O/F, thrust and specific impulse (I_{sp}) with time.

The students then developed a detailed set of drawings for their rocket motor thrust chamber and nozzle using SolidWorks. The thrust chambers were fabricated from aluminum round stock using a manual lathe. The nozzles were fabricated from graphite using a CNC turning machine. The HTPB and HTPB/Aluminum solid fuel grains were mixed and cured by each team. The HTPB was acquired from Aerocon Systems.

DEVELOPMENT OF THE ROCKET MOTOR TEST STAND

The semester design project for the Rocket Propulsion Course was conducted in parallel with a multidisciplinary design project in the Junior/Senior Engineering Clinic. The Engineering Clinic is a course that is taken every semester by engineering students from all four engineering disciplines at Rowan University. The objective of this particular Engineering Clinic project was to deliver a working 0 – 10 lb thrust rocket test stand that could be used to test the hybrid rocket motors that were designed and built in the Rocket Propulsion Course. The Engineering Clinic team consisted of two senior Mechanical Engineering students, one junior Mechanical Engineering student and one senior Electrical Engineering student.

Figure 1 shows the completed test stand with one of the rocket motors in test configuration. The test stand is capable of delivering gaseous oxygen (GOX) at 0 to 500 SLPM and 250 psig. The mass flow rate was measured and controlled using a Teledyne Hastings HFC203 Mass Flow Controller. Thrust is measured using an Omega LC101-25 0-25 lb load cell. Steady state chamber pressure is measured using an Omega Pressure Transducer and high response pressure data was measured using a PCB piezoelectric pressure transducer with a PCB 422E12 in-line charge converter. The ignition system consisted of dual automotive spark plugs which were energized using an ETP 300ST solid state induction coil.

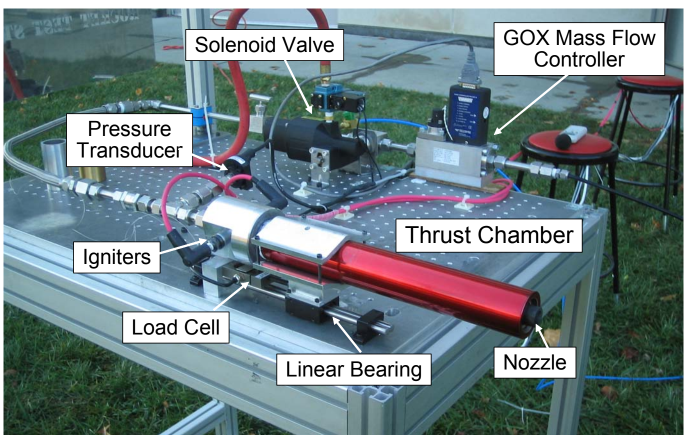

FIGURE 1
HYBRID ROCKET MOTOR TEST STAND WHICH WAS DESIGNED AND BUILT IN THE ROWAN UNIVERSITY ENGINEERING CLINIC

TEST RESULTS

Figure 2 shows an HTPB/GOX hybrid rocket motor during a test firing. Data acquired included instantaneous chamber pressure, thrust, oxygen mass flow rate and high speed dynamic chamber pressure to quantify the combustion stability. The data were acquired using an Agilent 34970A Data Acquisition/Switch Unit with GPIB interface and Agilent Benchlink software. The high response pressure transducer data were acquired using an HP 54645D digital storage oscilloscope and exported to Excel using Agilent Intuilink software. Each test lasted approximately 20 seconds. With these data, each team was able to measure specific impulse (I_{sp}), characteristic exhaust velocity (C*) and thrust coefficient (C_F) and compare these measurements to their analytical models, which predicted instantaneous O/F, C*, P_c, and thrust.

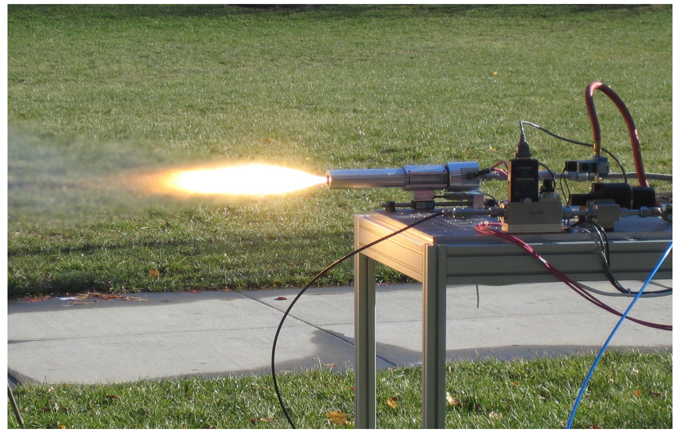

FIGURE 2
HTPB/GOX HYBRID ROCKET MOTOR TEST

Figure 3 shows the experimental results from the test firing shown in Fig. 2, along with the calculated results from the analytical hybrid rocket motor model for HTPB/GOX. The figure contains a plot of predicted and measure thrust and chamber pressure vs. time. The results show that the analytical model was reasonably effective in predicting the measured thrust and chamber pressure. The students also compared the theoretical specific impulse for their rocket designs to the measured specific impulse, with the latter quantity calculated from the following relationship:

$$I_{SP} = \frac{\int_0^t F dt}{g_o M_P} = \frac{\int_0^t F dt}{g_o \left(M_f + \int_0^t \dot{m}_{ox} dt\right)}$$

where I_{sp} is the specific impulse, F the instantaneous thrust, M_f the total mass of fuel consumed, m_{ox} the instantaneous mass flow rate and t the time.

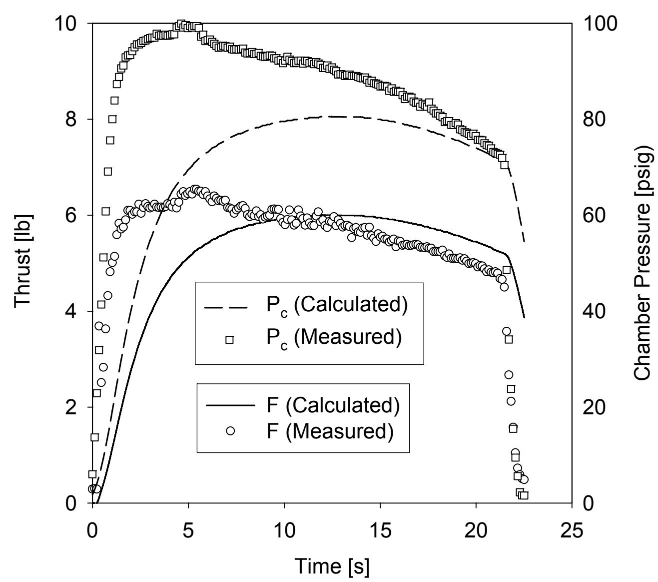

FIGURE 3
MEASURED AND PREDICTED CHAMBER PRESSURE AND THRUST FOR AN HTPB/GOX HYBRID ROCKET MOTOR