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FUNDAMENTAL PHENOMENA ON FUEL DECOMPOSITION AND BOUNDARY LAYER COMBUSTION PROCESSES WITH APPLICATIONS TO HYBRID ROCKET MOTORS

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SUMMARY:

An experimental study on the fundamental processes involved in fuel decomposition and boundary layer combustion in hybrid rocket motors is being conducted at the High Pressure Combustion Laboratory of the Pennsylvania State University. This research should provide an engineering technology base for development of large scale hybrid rocket motors as well as a fundamental understanding of the complex processes involved in hybrid propulsion. A high pressure slab motor has been designed for conducting experimental investigations. Oxidizer (LOX or GOX) is injected through the head–end over a solid fuel (HTPB) surface. Experiments using fuels supplied by NASA designated industrial companies will also be conducted. The study focuses on the following areas: measurement and observation of solid fuel burning with LOX or GOX, correlation of solid fuel regression rate with operating conditions, measurement of flame temperature and radical species concentrations, determination of the solid fuel subsurface temperature profile, and utilization of experimental data for validation of a companion theoretical study also being conducted at PSU.

DISCUSSION:

Hybrid rocket systems offer several advantages over their liquid and solid rocket counterparts. First, hybrid rockets require only half as much feed system hardware as liquid propellant rockets, and therefore display improved reliability. Second, since they are much less sensitive to cracks and imperfections in the solid fuel grain, hybrids have safety advantages over solid propellant rockets. Third, hybrid rockets can be throttled for thrust control and maneuvering. In addition, solid fuels are safer for manufacture, transportation, and storage. From a performance standpoint, hybrid rockets have specific impulse similar to those of liquid and solid rocket motors.

The experimental hybrid rocket program at PSU has been established to study the fundamental fuel decomposition and reacting boundary–layer processes (see Fig. 1) which occur in actual hybrid rocket motors or motor analogs. Figure 2 shows a schematic diagram of the overall hybrid test rig, including motor analog, gas supply system, and ignition system. A computer code was developed to assist in the design of the test motor. The code used a time–dependent continuity equation coupled with a chemical equilibrium code (CEC–76) to determine fuel regression rate, oxidizer–to–fuel mass ratio, chamber pressure, and gas temperature. Parametric studies were conducted to determine the effect of oxidizer flow rate, nozzle diameter, test time, and fuel composition on motor operating characteristics in order to meet the proper range of test conditions. Based upon the results of parametric studies and experience from previous experiments at Penn State, a windowed, 2–D hybrid motor was designed. Figure 3 shows a partial assembly drawing of the hybrid motor analog. The motor utilizes either two opposing fuel slabs or one fuel slab with an opposing inert slab and may operate with either gaseous or liquid oxygen as the oxidizer source. Interchangeable exit nozzles provide partial control of chamber pressure. The two sets of opposing windows can accommodate a variety of instrumentation and diagnostics for measuring fuel regression rate, gas velocity, flame temperature, and species concentrations. At this point, a large portion of the motor has been constructed.

The gaseous oxygen supply system shown in Fig. 2 consists of a main feed line and a nitrogen purge. Remotely operated ball valves initiate and terminate the flow of oxygen, while a critical flow venturi maintains a steady mass flux through the main line. An upstream thermocouple and pressure transducers located on either side of the venturi give a measure of the oxygen flow rate. The flow rate will be preset for each test. GOX and GN_2 filters prevent contamination of the system.

Based upon a literature search and comparative study of various ignition systems, an igniter was designed as shown in Fig. 2. The ignition system consists of a high–pressure gaseous oxygen/methane premixed torch and a solid–propellant pilot flame. The solid propellant strands are ignited electrically using nichrome wires connected to an AC transformer. Remotely operated solenoid valves control the flow of oxygen and methane. Check valves and vents prevent the contamination of the gas bottles and over pressurization of the system. Gaseous nitrogen is used to purge the ignition system after each test. The ignition system has been constructed and tested successfully with feed pressures up to 550 psig. It is expected that the GOX/CH_4 torch will ignite the fuel slabs and be shut off before the gas pressure in the motor exceeds a pre–specified critical pressure.

After a thorough literature search on spray injectors, a showerhead design was suggested for the LOX injector. This design employs multiple rows of pressure atomized jets aligned parallel to the fuel slab(s). This type of design has been well studied, and such an injector is relatively easy to manufacture. A prototype single–row injector was constructed and tested in an existing pressure chamber. Flow visualization studies using a video camera and a strobe light have been made to determine the break–up characteristics and degree of atomization of a water jet through the injector. This study is helpful in selecting the injector size for the pre–specified range of feed pressures.

A control panel for operating the hybrid motor, GOX supply line, and ignition system has been designed and assembled. The control panel will display a mimic diagram of the entire hybrid motor analog system, as well as switches to arm the GOX supply and ignition system, and to control the various remote valves and the solid propellant pilot flames. The tests will be automated using an IBM PC/AT computer and data acquisition and control board. The control program is currently being written and tested.

Several diagnostic techniques will be used to measure the properties of interest. The fuel regression rate will be deduced from images obtained by a high speed movie camera (HYCAM) coupled with a real–time x–ray radiography system. Radical species (such as OH) concentration and flame temperature will be measured as a function of longitudinal location using UV/visible absorption spectroscopy. Both static and dynamic pressures in the motor will be measured using pressure transducers.

The subsurface temperature of the solid fuel will be measured by an array of R–type fine–wire thermocouples which are embedded at pre–determined depths in the solid fuel slabs prior to testing. Several 25μm micro–thermocouples were manufactured, soldered to extension wires, and cast inside 0.25 inch diameter fuel plugs. Since the micro–thermocouples are easily damaged, it is expected that casting them inside small fuel plugs, then casting the plugs inside the fuel slab, will produce better results than simply inserting the thermocouples into the fuel while it is curing. Eight thermocouple–containing fuel plugs will be cast into each HTPB fuel slab.

In order to fabricate solid fuels with high quality and to achieve short curing time, several fuel curing tests were conducted using R–45M homopolymer from Elf Atochem and a curing agent of Isonate 143L (MDI) from Dow. Since R–45M has a hydroxyl value of about 0.73 meq/g and Isonate 143L has an amine equivalence of 144.3 g/eq, the weight of Isonate 143L used was approximately equal to 11% of the weight of R–45M (assuming an NCO/OH ratio of 1.05). The fuel curing time was about 8 hours, nearly an order of magnitude shorter compared to the combination of R–45M, IPDI curing agent, and dibutyltin dilaurate catalyst. Approximately 35 gallons of R–45M have been received from Elf Atochem to cast the fuel slabs for motor tests using HTPB fuel processed at the Penn State University.

In the above fuel curing process, a layer of Teflon release agent (obtained from the Miller–Stephenson company) was coated on the surface of fuel casting molds and allowed to dry thoroughly before fuel casting. After curing, the fuel slabs were easily removed from the molds. In the near future, the large fuel molds which will be used to cure fuel slabs for the tests, will be professionally coated with a Teflon release agent by Hitempco Southwest. As soon as the fuel casting molds and sample holders are complete the portion required by industrial companies will be shipped to NASA/MSFC or directly to the NASA designated companies.

Testing of the hybrid motor analog will commence after the motor and GOX supply system have been completed. Table 1 shows the range of proposed test parameters. The first series of tests will utilize solid HTPB fuel and GOX. Later tests will use fuels supplied by industry. After all tests with GOX have been completed, the chamber will be moved into the Cryogenic Laboratory at the High Pressure Combustion Lab in order to use the existing LOX supply and control system for LOX/solid fuel tests.

Table 1. Range of Test Parameters

Solid Fuel Composition:	Baseline HTPB and NASA Fuels
Chamber Pressure:	300–900 psi
Oxidizer Flow Rate:	up to 1.5 lb/s
Initial Temperature:	70° F nominal
	35° F low
	90° F high

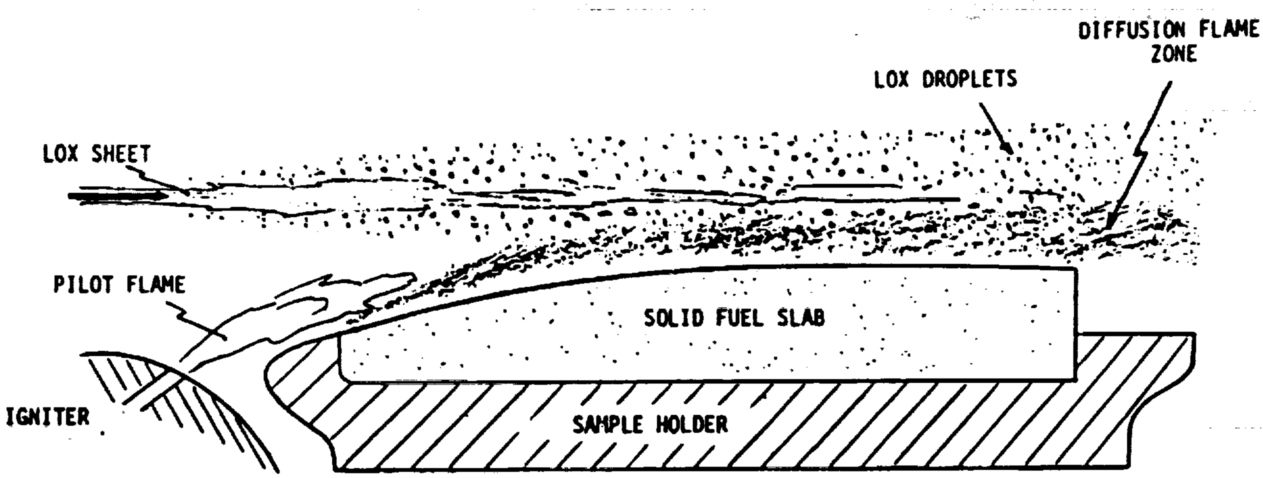

Fig. 1 Schematic Diagram of the Diffusion Flame Zone Adjacent to the Solid Fuel Slab

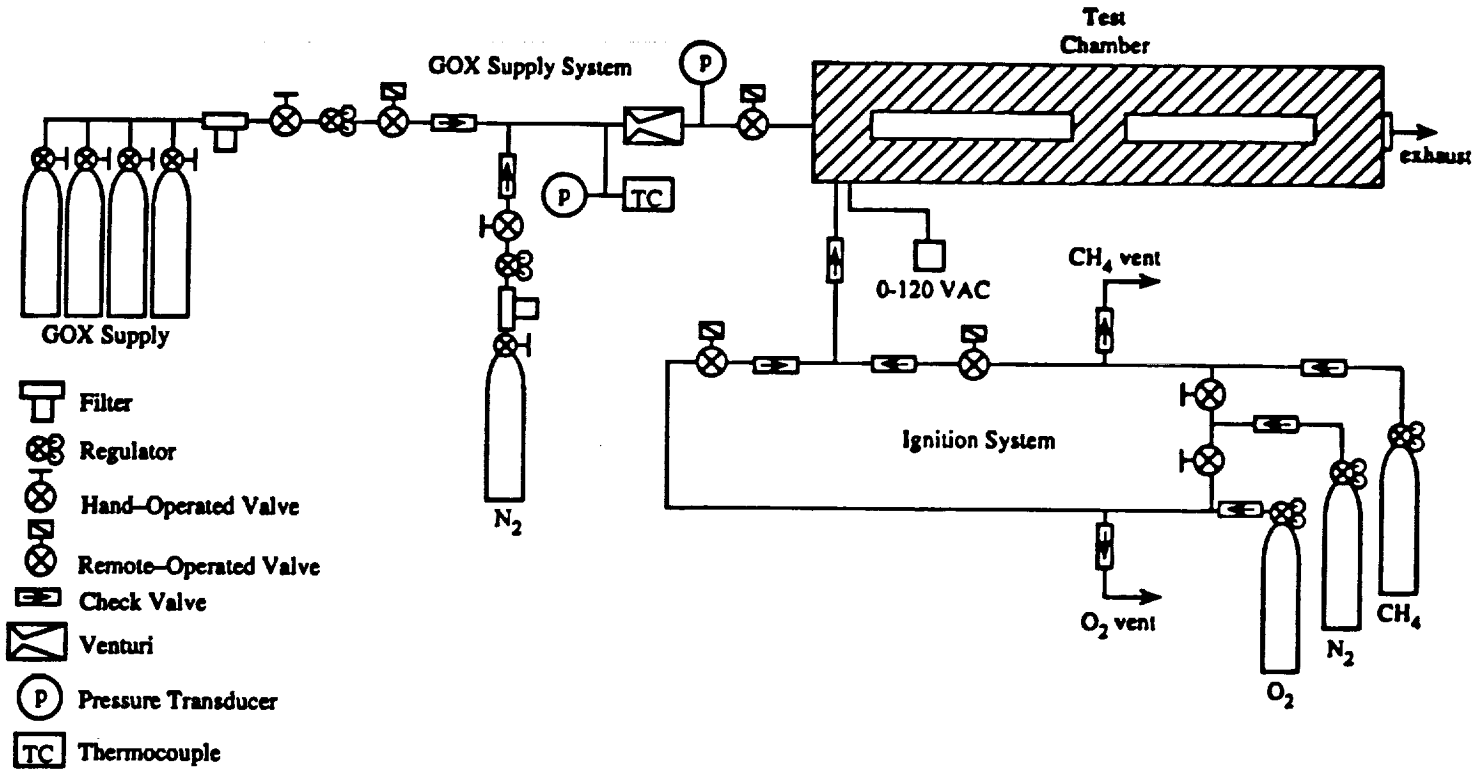

Figure 2. Penn State Hybrid Test Rig

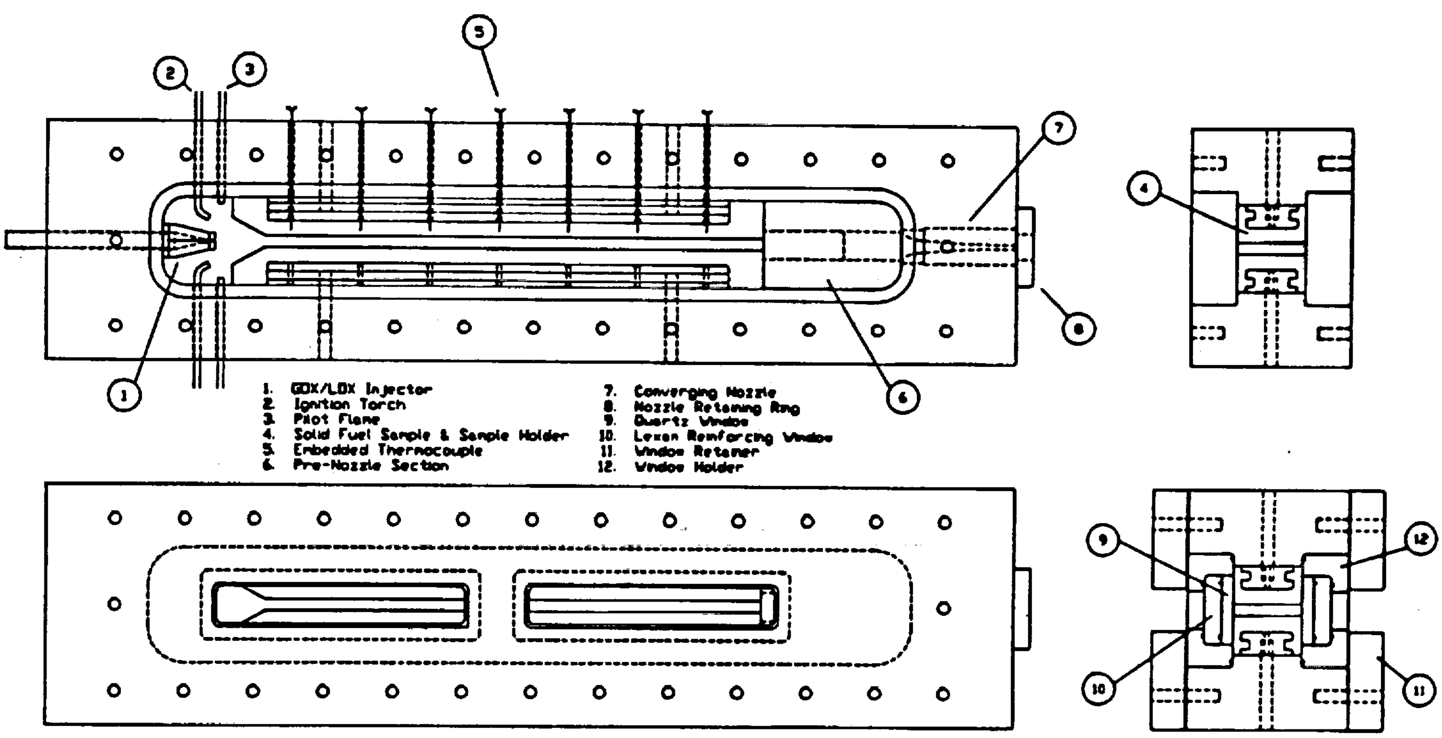

Fig. 3 - Partial Assembly Drawing of Hybrid Test Chamber