Purdue University Promotes Propulsion Education and Research through Unique Testing Facilities

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Purdue University has a long tradition in propulsion research, and its unique facilities enable hands-on education in combustion and aerospace sciences. A significant part of propulsion testing facilities at Purdue are located at a remote location, away from the main part of campus, on a 24-acre site adjacent to the Purdue University Airport. Rocket propulsion testing at Purdue began in 1948, under the direction of Dr. Maurice Zucrow. The Advanced Propellants and Combustion Laboratory (APCL) houses two control rooms and three test cells (Cells A, B, and C) for propulsion testing, fuel coking studies, and propellant development. Another rocket test cell (Cell T) is now operational in the Propulsion Laboratory. Test firings are conducted and observed from the control rooms. In addition, there are several small-scale experimental labs throughout the Zucrow complex.

Gelled Propellant Lab (GPL)

The GPL is Purdue's newest propulsion laboratory being developed in support of an Army Research Office (ARO) Multidisciplinary University Research Initiative (MURI) program on spray and combustion of gelled hypergolic propellants, which was awarded last year to Purdue and its partners. The GPL houses a control room and a laboratory space dedicated to small-scale testing with hypergolic propellants such as NTO, IRFNA, and hydrazine-based fuels. The versatility of the mechanical and data acquisition systems as well as the dedicated air ventilation and monitoring systems installed at GPL make this laboratory particularly well-suited for testing of hypergolic systems and fire/vapor suppressant systems, as well as other small-scale experimental activities.

LOX-LCH$_4$ Facility

The LOX-LCH$_4$ facility is being developed to provide a known-temperature liquid cryogenic fluid to a test article. Standard gaseous oxygen and methane cylinders are used to supply pressurized gases into cyrogenic chilling tanks to produce and store liquid propellants for test operation. Each system can be independently temperature-controlled with a goal to deliver specified temperature propellants to the test hardware. The facility is designed to test small-scale thrusters and ignition work in addition to fundamental instability research of LOX-LCH$_4$.

Solid Propellant Mixing and Combustion Lab

Purdue's solid propellant mixing facility utilizes a Ross model DPM-1 Quart double planetary mixer that has a mixing range of ½ pint to 1 quart with stirrer speeds of 22-98 rpm with cooling or heating control, and vacuum to about 0.5 psia. The Ross mixer can be operated remotely from a control room. The facility includes two windowed pressure vessels (Crawford bombs) for combustion studies of propellants and energetic materials. Pressures up to 6000 psi can be considered. Sapphire windows allow access to infrared access, and a top window of one of the vessels is configured for the use of a Zinc Selenide (ZnSe) top window that allows ignition studies using a CO_2 laser. High-speed digital microscopic imaging and visible/IR spectroscopy are used in combustion studies. Electostatic discharge (ESD) and impact testing is used to quantify sensitivity of new propellants. Material ball milling, cutting, and polishing, along with microscopy, are also available for sample characterization. An environmentally controlled glovebox is used to keep nanometals pristine. A light gas gun, explosive blast chambers, and initiator testing facilities are also currently used. Purdue also maintains active Class 1.1 and 1.3 bunkers for remote storage of energetic materials as part of the Zucrow Laboratory complex. Many other small-scale laboratory research projects are also located at Zucrow Labs, including hydrogen storage, combustion, spray dynamics, and fluid dynamics.

High Pressure Lab (HPL)

Originally constructed in the mid-1960s in support of the Apollo program, HPL provides the most substantial capabilities for rocket and airbreathing combustion and nozzle studies with two large test cells classed to 10,000 lbf thrust levels. A 6000 psi nitrogen system serves for pressurizing facility tanks, and 5000 psi liquid oxygen, gaseous hydrogen, kerosene, hydrogen peroxide, and cooling water capabilities exist to the 10,000 lbf thrust level. A gas-fired heat exchanger provides airflows heated to 1000^o F at flowrates on the order of 10 lb/s to simulate airbreathing combustor inlet conditions, and roughly 5 tons of high-pressure air storage is available from the lab air system. There are also several unique large-scale testing facilities at Zucrow Labs. Pulse denotation and high-pressure gas turbine combustor test rigs are currently in place at HPL. The airbreathing combustor rig provides optical access for diagnostic access to the combustor. The HPL Annex is the newest building within the HPL complex. This 1400-sq ft structure provides large

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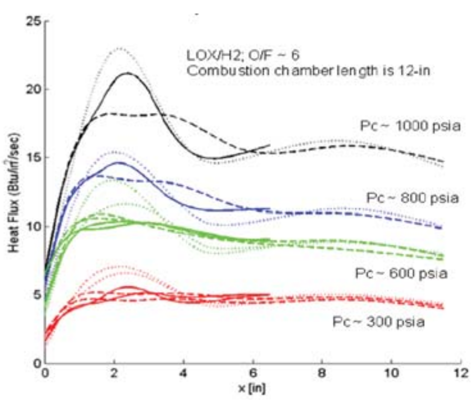

Figure 1. Hydrocarbon film cooling test on 10 klbf thrust stand at Purdue High Pressure Laboratory (left). On the right, is a fitted heat flux measurement for a HO combustor. Different lines within each pressure grouping refer to measurements at different azimuthal locations.

flow capabilities for airbreathing combustion and nozzle experiments (see Ref. 1 for details).

In the past decade or so there has been a reinvigoration of the facilities and increase in personnel at Purdue directing efforts in propulsion, as well as in related areas of energy and combustion. Additional details about the facilities can be found at https://engineering.purdue.edu/AAE/Research/ResearchFacilities/LabFacilities, https://engineering.purdue.edu/Zucrow/index.html and in Refs. 2 and 3.

Current Research Topics

Research pertaining to propulsion is inherently multidisciplinary and therefore includes elements from numerous organizations within the Schools of Engineering and Science at Purdue University. More than a dozen professors, specifically within the Schools of Mechanical Engineering (ME) and Aeronautics and Astronautics (AAE), are involved with propulsion research at Purdue. This faculty advises over 75 graduate students and postdocs in the AAE and ME departments with annual research expenditures in the $5 million/year range. The faculty and students are supported by several staff members, including a Senior Engineer and a Technical Services Supervisor. Recently, testing and collaborative research programs have been conducted with funding from Rolls Royce Allison, Aerojet, Pratt & Whitney, Northrop Grumman Space Technologies, Precision Combustion Inc., General Kinetics, ATK, NASA Marshall Space Flight Center (MSFC), Stennis Space Center (SSC), Dryden Flight Research Center (DFRC), and Glenn Research Center (GRC), Orbital Sciences Corporation, Air Force Office of Scientific Research (AFOSR), Army Research Office (ARO), Office of Naval Research (ONR), Naval Research Office (NRO), Missile Defense Agency (MDA), Ensign-Bickford Aerospace and Defense Company (EBA&D), Defense Advanced Research Projects Agency (DARPA), and others. Liquid/gelled, solid propellant, and airbreathing propulsion are all being studied.

Additional information about the faculty and staff is available on the following Web sites: https://engineering.purdue.edu/Zucrow/People/faculty.html; https://engineering.purdue.edu/AAE/Research/ByProfessor/Propulsion; and https://engineering.purdue.edu/Zucrow/People/index.html.

Liquid and Gelled Propulsion

Research in liquid rocket propulsion includes studies of the ignition and chemical kinetics of hypergolic propellants; gelled propellants; development of a combined analytical-experimental-computational testbed for combustion instability; and detailed computations of the hydrodynamics inside injector elements, rocket-based combined-cycle engines, and measurement of heat flux in a few-thousand lbf thrust multi-element oxygen-hydrogen combustor.

Large-scale rocket studies are conducted on the 10,000 lbf thrust stand in the High Pressure Lab (shown in Fig. 1) during a liquid hydrocarbon film cooling test conducted for the Air Force Research Laboratory (AFRL) and its SBIR contractor, Sierra Engineering. Axially- and circumferentially-resolved heat flux measurements in a seven-element HO combustor at 1000 psia are also shown in Fig. 1; measurements like these are being used by NASA to learn how to accurately compute the 3-D reacting flowfield inside high-pressure rocket combustors.

A major effort to develop a methodology for a priori prediction of liquid rocket combustion instability comprises a hierarchy of analysis, experiments, and computations.

Experiments using an unstable model rocket combustor are used to validate the high-fidelity (e.g., LES) computations, and those results are used to derive reduced-order combustion response models for use in engineering-level models for stability prediction. This work is being conducted for AFRL, AFOSR, and its subcontractor, INSpace. Studies to examine the combustion stability of LOX/LCH_4 engines for NASA lunar missions are also underway.

Most recently, Purdue was awarded a MURI from ARO for a comprehensive study of gelled propellants. The program includes the development of models for gel rheology and internal flow, as well as studies of spray formation, hypergolic ignition, and drop burning of the gelled propellant. The culmination of this program is the integration of these results into a time-accurate computational model of rocket combustor processes, ranging from flow into the injector elements to combustion product flow out the nozzle, that is validated by a benchmark experiment conducted at the Gelled Propellant Laboratory.

Solid Propellants and Energetic Materials

Although solid propellant studies are not new to Purdue, there has been a recent increase in solid propellant research. Currently, there are seven graduate students working in this area. With the development of propellant mixing, combustion, and characterization capabilities, researchers can now systematically develop and study new solid propellants, as well as produce standard propellants for testing. Some current projects that have been funded include a study of erosive burning (NASA); development and characterization of a new propellant binder system (MDA); high burning rate propellants (EBA&D); dynamic combustion of nano-aluminized propellants (AFOSR-STTR); development and testing of advanced propellants, including Al-ice (ALICE) propellants (AFOSR/NASA); and aluminum droplet dynamics in realistic environments (AFOSR-STTR). Related research topics on energetic materials, including nanoscale composite energetic materials, are actively pursued in laboratories in the Propulsion and Combustion Buildings.

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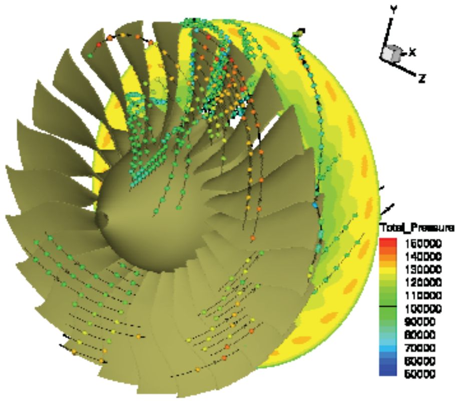

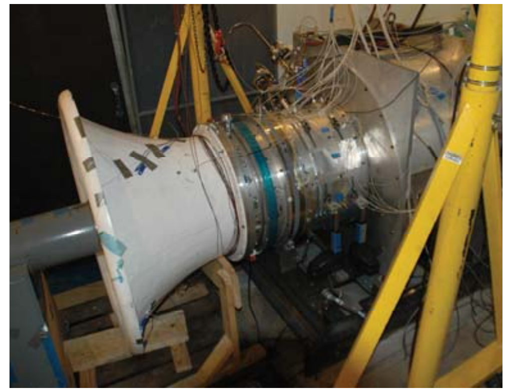

Figure 2. 3-D Fan Performance CFD Analysis Conducted for a Supersonic Business Jet Flowfield (left). On the right is an image from Purdue's compressor research facility aimed at investigating tip leakage effects on the last stage of a highly loaded Rolls-Royce outlet guide vane and pre-diffuser configuration.

Airbreathing Propulsion

The propulsion group at Purdue University maintains a substantial research effort in airbreathing propulsion. Purdue also maintains the nation's only Rolls-Royce University Technology Center (UTC) in the area of high Mach propulsion. Ongoing UTC work involves the study of high temperature fuel systems and fuel coolant configurations to provide turbine cooling air for high Mach applications. Studies in coking of JP fuels, endothermic potential of JP-10, fuel/air heat exchangers, fuel system thermoacoustic instabilities, and injection and mixing of supercritical fuels are currently underway within the UTC. In addition, a large group within the UTC is studying inlet and exhaust systems for supersonic business jet applications with Rolls-Royce and partner Gulfstream Aerospace Corp. Computational studies (Fig. 2) are being conducted on both inlet and exhaust system concepts, and advanced configurations are being studied to enhance propulsion system performance and to minimize noise. A substantial test facility (BiAnnular Nozzle Rig, or BANR) has been developed for this project to support hotfire testing of turbofan nozzle configurations. The BANR can simulate turbine and fan exit conditions to nozzle pressure ratios of 6 with overall flows of 30-50 lb/s.

Experimental facilities are also available for studying turbomachinery flows. A unique high-speed rotating compressor research facility has received recent driveline upgrades, including 1400 hp motors controlled with variable frequency drives for each of the three high-speed test cells. Current research efforts are investigating flow through a high-performance Rolls-Royce centrifugal compressor assembly. A gearbox featuring a gear ratio of 30:1 provides the required 52,000 rpm shaft speed. Axial compressor research is aimed at investigating rear core performance issues, including efforts to desensitize tip leakage flows from the relatively high clearances experienced in the geometrically small stages in the rear of the core. The last stage of a Rolls-Royce compressor followed by a pre-diffuser and combustor plenum features a highly loaded outlet guide vane and adjustable rotor tip clearance rings. The third test cell is dedicated to investigating techniques to mitigate forced response issues in a 3-stage compressor designed by GE-Energy.

Of course, the most important product of Purdue's propulsion program is its well-educated and trained student body. Purdue is one of the few schools to offer propulsion as a major field of study and courses in airbreathing and rocket propulsion at both the undergraduate and graduate level. These unique educational opportunities provide Purdue graduates with the tools necessary for advancing the propulsion state of the art as professional engineers. Recognition of Purdue's position and impact on the field of propulsion was evidenced last year when the University topped the *Aviation Week* list of preferred institutions from which the aerospace and defense industry recruits.

References

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