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Research Capabilities in Propulsion and Combustion Science at the Georgia Institute of Technology

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I. Introduction

The Propulsion and Combustion (P&C) research group at the Georgia Institute of Technology (Georgia Tech) is uniquely positioned to fully support and advance the nation's environmental, economic, and security initiatives. The research group maintains an accomplished infrastructure with a manifold of computational and experimental capabilities conveniently located at Georgia Tech. The P&C group considers itself a multi-disciplinary team comprised of intellectual-talent leading in the areas of combustion science, power generation, aircraft and in-space propulsion systems, and plasma physics. The P&C team can leverage its test facilities, specialized personnel, and resources to address a wide range of challenges observed in modern propulsion technology and energy systems.

Notable stakeholders in government and industry sectors continue to collaborate with the P&C group at Georgia Tech for technology development and innovation based on global trends. One example is the emerging space-based infrastructure and the new markets in the telecommunications landscape. Changes in this domain have motivated the commercial space sector to revisit launch vehicle platforms and in-space propulsion systems. Various commercial space companies now seek to integrate high-power electric propulsion (EP) devices on their satellites to reduce launch costs [1]. Other companies envision fully democratizing the internet by connecting the remote areas through a network of low-Earth orbiting satellites in which propulsion devices will play an important role [2]. In addition to industry trends are environmental patterns prompting stakeholders to reduce emissions of fossil fuels and identify alternative energy sources. Typical research objectives along this front aim to increase the efficiency of propulsion devices and gas turbine engines. As these paradigmatic shifts in the world continue to occur, the P&C research group at Georgia Tech leverages its current computational and experimental test facilities while continuing to expand its capabilities for future endeavors.

The Ben T. Zinn Combustion, High-Performance Computing, and High-Power Electric Propulsion laboratories at Georgia Tech are highly capable research facilities committed to supporting critical initiatives set forth by our nation's leadership. Past accomplishments coupled with a proven academic curriculum that includes combustion science, propulsion, fluid mechanics, and plasma physics enhance the test operation experience and technical aptitude of the research personnel. These laboratories have made many contributions in combustion instability, computational modeling of combustion processes, and plasma sheath physics. However, much of their success is attributed to the specialized capabilities, be it unique testing facilities or high performance computing techniques offered by each laboratory in the P&C group. Ultimately, it is the world class faculty and research facility

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capabilities that enable the Ben T. Zinn Combustion Laboratory (Combustion Lab), High-Performance Computing Laboratory (CCL), and the High-Power Electric Propulsion Laboratory (HPEPL) to perform a variety of experiments advancing the interests of industry, government, and academic partnerships. This manuscript provides a comprehensive overview of the research capabilities offered by the P&C group laboratories at Georgia Tech.

II. Ben T. Zinn Combustion Laboratory Facilities

The Ben T. Zinn Combustion Laboratory, pictured in Fig. 1, is located in the North Avenue Research Area (NARA) at Georgia Tech. The 18,000 ft^2 laboratory facility is valued at over $8 million and continues to grow its capabilities in energy systems and combustion science experimentation [3].

Figure 1. Ben T. Zinn Combustion Laboratory at Georgia Tech

A. Combustion Laboratory Facilities Overview

The test facility consists of an open laboratory with a variety of test stations, each equipped with electrical power, intermediate-pressure air supply, pressurized natural gas, domestic and chilled water supplies, and an exhaust system capable of handling up to 25 MBtu/hr. The test facility also consists of isolation rooms, which are equipped similarly to the open laboratory, but which are optically and acoustically isolated from the rest of the test environment. The facilities also use four high-pressure test cells, each equipped with high-pressure, pre-heated air and high-pressure natural gas, in addition to the resources listed for the open laboratory stations.

The Combustion Lab has a total stored air mass of 7,350 lbs. at a max pressure of 2800 psi, approximately 100,700 standard cubic feet (SCF). The air system can deliver pressures up to 720 psi to the four high-pressure rooms within the facility at ambient temperatures up to 1,000 °F. The maximum air flowrate is more than 1000 lbs./s for short bursts limited by pipeline size, delivery pressure, and initial storage pressure. The test facility is capable of providing 250 psi and 125 psi air to all areas of the laboratory.

Catering to a wide-range of combustion science applications, the Combustion Lab employs gaseous, liquid, and multi-fuel delivery system. Arbitrary air and fuel combinations include hydrogen, carbon monoxide, carbon dioxide, nitrogen, methane, oxygen, and other gases as needed. The laboratory is also equipped for liquid fuels, such as Jet A. Fuel blend volumes are available from individual bottles or two full size trailer storage bays for additional high capacity fuels [3].

The Combustion Lab is fitted with a small machine shop area, which includes a lathe, mill, saws, grinders, welders, and other machining tools for researchers to use. The School of Aerospace Engineering, as well as other on-campus machining resources, provide fully-staffed machine shops for fabrication, assembly, repair, and modification of individual components or entire mechanical devices. These on-campus machine shops have full-time machinists trained in using computer numerical control (CNC) mills, CNC lathes, wire electrical discharge machines (EDM), water jet cutting system, welding equipment, and other machining tools [4].

To continue fostering safe work environments for its researchers, Georgia Tech has implemented an integrated gas monitoring system in all buildings where dangerous gases are used. This system monitors all laboratories for gas leaks, gas releases, ventilation failures, and power failures and alarms locally to warn users as well as sending messages alerting Georgia Tech Environmental Health and Safety and Georgia Tech Police [5].

The Carbon Neutral Energy Solutions (CNES) Laboratory is designed to foster industry collaboration and support translational and pre-commercial research in clean, low carbon energy technologies. Research spans all aspects of the energy cycle from production and generation to distribution and utility and focused on addressing our most pressing energy and environmental challenges. Core research conducted within the laboratory includes, solar technologies, combustion, gasification, catalysis and bio-catalysis, as well as carbon capture and sequestration. The proposed capabilities for the 3,000 ft^2 high-pressure testing facility would supply continuous air at 500 psig, at 10 lb./s, and up to 1400 °F. The facility would have multi-fuel and oxy-fuel capability including liquid fuels, natural gas, hydrogen, nitrogen, etc. [6].

B. Combustion Processes Diagnostics

Researchers at the Ben T. Zinn Combustion Laboratory are well-practiced in the major combustion diagnostic techniques. For example, high-bandwidth optical diagnostics such as particle image velocimetry (PIV), planar laser induced fluorescence (PLIF), high speed chemiluminescence imaging, laser Doppler velocimetry (LDV), and Phase Doppler Particle Anemometry (PDPA) are very popular techniques readily employed throughout the test facility. Additionally, basic flow instrumentation for pressures and temperatures are used together with subcritical orifices and/or critical orifices to meter flow rates of gases, often at elevated temperatures. Some of the major equipment and diagnostic capabilities are detailed below.

1. Diagnostic Equipment

Many of the key diagnostic techniques are enabled by a wealth of shared diagnostic equipment within the test facility. This equipment consists of high speed continuously pumped solid state lasers, low speed Q-switched solid state lasers, and high and low speed tunable dye lasers. A large collection of high speed cameras is available, including several NAC GX-3 cameras, a Photron SA1.1, a Photron SA3, a pair of Photron SA5's, a pair of Photron SAZ's. Several UV-sensitive image intensifiers are also available, including HiCatt systems, a high speed IRO, and custom-built options. Low repetition rate intensified charge coupled device (CCD) cameras are also present. These laser and camera systems are accompanied by a number of oscilloscopes, multi-channel timing/synchronization tools, and a suite of opto-mechanics. PIV measurements are supported with several licenses of the latest DaVis software from LaVision for implementation of the PIV algorithm for vector field calculation. Gas sampling is conducted with two Horiba portable gas analyzers, including a Horiba PG-350.

2. Chemiluminescence

Chemiluminescence imaging is used to visualize combustion reaction zones, often at high repetition rates. High speed imaging of OH* and CH* radicals is most popular. Several high speed cameras, listed in the Diagnostic Equipment section, are available for measurement of both of these species. Several optical filters are available for CH* imaging, and UV-sensitive high speed intensifiers and optical filters are available for OH* imaging. Fig. 2 shows an example of this imaging technique.

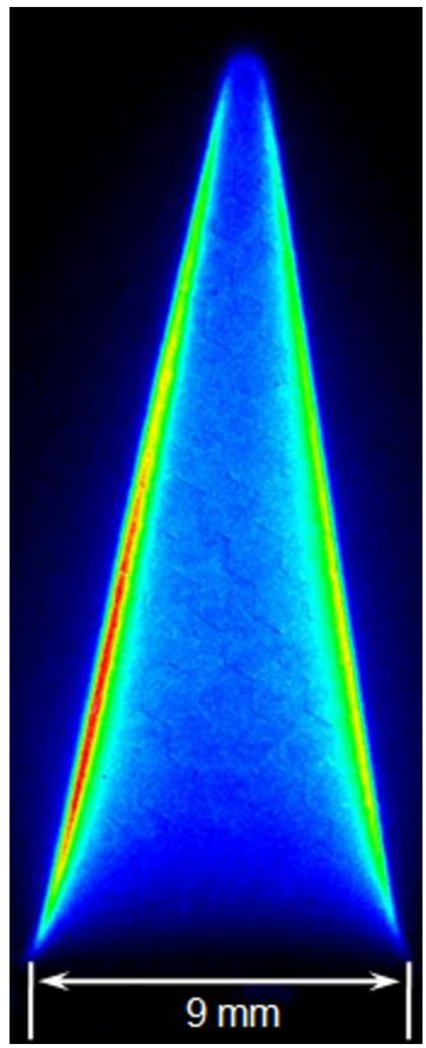

Figure 2. Chemiluminescence image of a C_3H_8 – air Bunsen flame at 650K, 1 atm (Φ=1.2)

3. Schlieren Illumination Equipment

In certain circumstances, visualization of fluid boundaries and flow features are necessary and can take advantage of density gradients using a Schlieren diagnostic. The laboratory is well equipped to perform Schlieren using continuous wave or pulsed light sources and with a range of collimating and focusing optics. Coupled with the imaging resources in the laboratory, high speed acquisition is performed for time resolved videos of evolving density features. This diagnostic is primarily applied to experiments focused on high speed flows, forced ignition, and spray physics.

4. PIV

The PIV measurements are sometimes acquired at low sampling rates (tens of Hz) for independently sampled flow statistics, and may be sampled at high sampling rates up to 40 kHz for time-resolved measurements. For both high repetition rate and low repetition rate PIV, stereoscopic PIV is often the setup of choice (as opposed to two-component PIV), particularly for highly three-dimensional flows and combustors consisting of curved glass features.

5. PLIF

PLIF measurements are used as flow/mixing visualizations for flows seeded with acetone. In addition, OH PLIF is used for combusting flows at either low (tens of Hz) or high (tens of kHz) sampling rates to visualize reaction fronts. These measurements are often co-planar with and synchronized to a PIV measurement. Researchers also have experience with CH PLIF and Formaldehyde PLIF at lower sampling rates.

6. Hotwire

Hot-wire anemometry is a common choice for single-point velocity measurements, particularly for characterization of turbulence. To obtain highly time-resolved point-measurements of velocity and temperature in mostly non-reacting flows, the laboratory offers wire-probe measurement capabilities. Dantec and LabVIEW data acquisition systems with dedicated calibration units compose the backbone of the system. Probes range from standard freestream and boundary-layer hot-wires to miniaturized nano hot- and cold-wires. Sample sizes for this technique are more or less unlimited and are recorded at frequencies up to 160 kHz. Using multi-wire probes or multi-position techniques, multiple velocity components are resolved as well as a wide range of relevant statistical quantities pertaining to turbulent flow. Within the laboratory the technique has been used to characterize a wide range of subsonic and supersonic flow fields with turbulence intensities of up to 25% of the freestream velocity.

7. LDV-PDPA

In high-temperature flows (such as combustion environments) where the hot wire technique is not practical, three-component LDV is a common choice for single point velocity measurements. In addition to gas-phased velocity statistics, PDPA measurements are often used to gather droplet velocity and size statistics in liquid-fueled combustors.

8. Pitot—static

The Combustion Lab has the capability to take measurements using a pitot tube. A pitot tube gives an accurate measurement of the flow velocity in a subsonic environment. The pitot tube is considered an intrusive measurement as it sticks a physical device into the flow field. However, this is also a powerful measurement in an incompressible flow as the governing physics are quite simple. This allows for high sampling rates and real time analysis of a point velocity measurement in the flow field.

9. Acoustics and Combustion Dynamics

For acoustic measurements, several acoustic probes are often used together to sample high frequency pressure oscillations that are analyzed to reconstruct an acoustic field, measure impedance boundary conditions for simulations, monitor combustion dynamics, etc.

10. Super Rapid Compression Machine

Another counter facility for combustion chemistry study is the Georgia Tech Super Rapid Compression Machine (SRCM). The SRCM, as shown in Figure 3, features a two-piston design to compress test combustible mixture to high temperature high pressure condition within approximately 3 ms. The full optical access of the combustion chamber allows for multidimensional diagnostics.

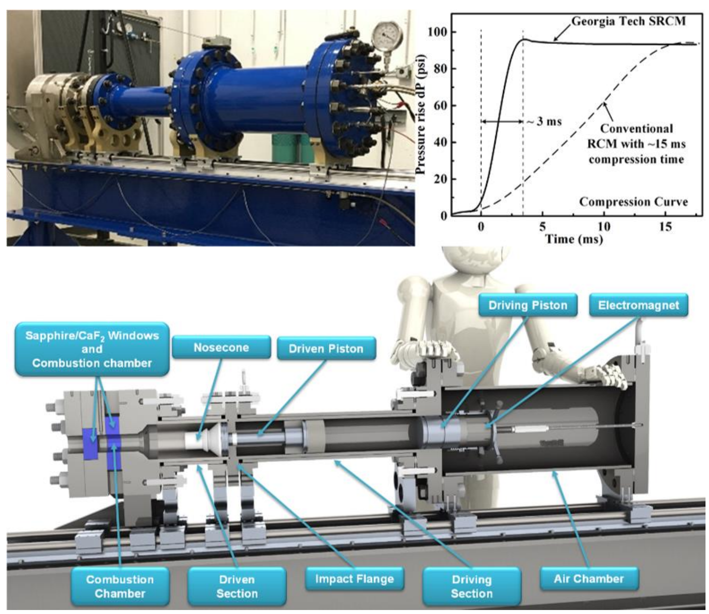

Figure 3. Super Rapid Compression Machine at Georgia Tech

11. Diffused Back Illumination

Diffused back illumination (DBI) is used to attain highly spatial and temporal quantitative information about spray break-up processes and soot production. DBI measures the scattered light intensity after interacting with the spray. Using a pulsed LED light source, engineered diffusers, and a high speed camera, 2-D scattering maps of the spray are developed. This diagnostic is particularly useful in attaining quantitative, highly spatial and temporal-resolved soot or spray break-up data [12].

C. Computational Combustion Laboratory

Complementing the experimental test facilities is the High-Performance Computing Laboratory at Georgia Tech. Established by Prof. Vigor Yang in December of 2009, the research group has developed several advanced numerical tools to investigate various research projects related to propulsion and power-generation systems, including combustion dynamics in liquid rocket engines, combustion stability modeling and design, plasma assisted combustion, and smart functional nano-energetic materials. These projects are facilitated by high performance computing facility in Prof. Yang's group. The facility consists of four AMD-based Linux clusters and presently includes 129 nodes and 6000 processors with superior scalability. The clusters are well maintained by the Partnership for an Advanced Computing Environment (PACE) at the Georgia Institute of Technology.

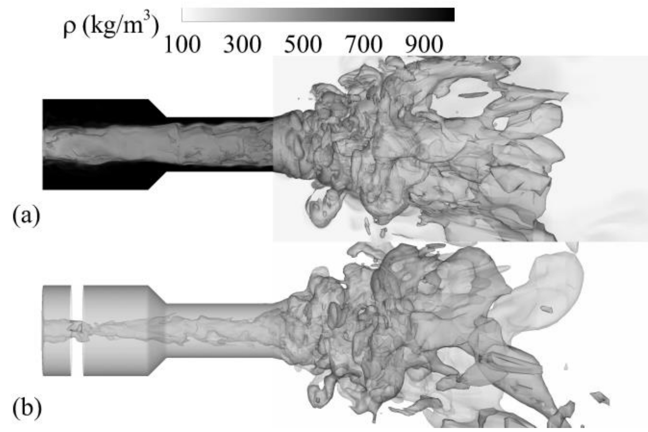

Figure 4. Flow dynamics of LOX swirl injector in RD0110: (a) density field with two iso-surfaces: ρ = 532 and 250 kg/m (b) iso-surface of azimuthal velocity of 4 m/s; P = 100 atm

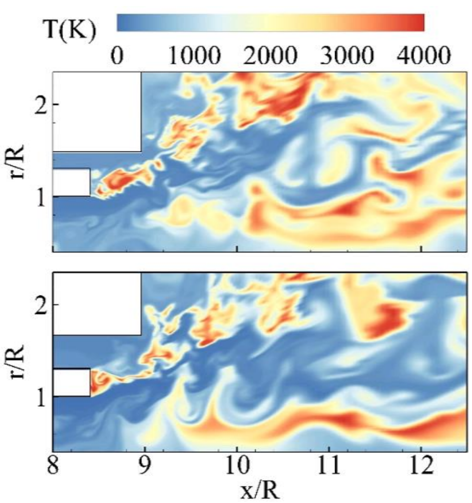

Figure 5. LOX/kerosene combustion in a bi-swirl injector (RD0110)

1. Fundamental Processes in Liquid Rocket Engines

A numerical software has been established, which aims to perform high-fidelity simulations of mixing and combustion dynamics in contemporary propulsion and power generation systems, including air-breathing and liquid-propellant rocket engines. The basis of this software is the three-dimensional large-eddy-simulation (LES) code developed under the Air Force Office of Scientific Research (AFOSR) sponsorship in the past 15 years. The accuracy, robustness, and efficiency segments of this predictive capability have been constantly improved in recent years. The theoretical and numerical framework is capable of treating turbulent, chemically reacting, multi-phase flows over the entire fluid thermodynamic state of concern [14, 15]. A unified treatment incorporating fluid mechanics, thermodynamics, and transport phenomena has been developed and implemented to study a variety of supercritical fluid and combustion problems [16, 17], including liquid oxygen (LOX)/methane [18], gaseous oxygen/hydrogen [19], and LOX/RP-1 [20-22] mixtures (Figs. 4 and 5), etc.

2. Combustion Stability Modeling and Design

An interdisciplinary team with extensive expertise in supercritical combustion, combustion instabilities, reduced-basis modeling, statistics, uncertainty quantification, and machine learning are assembled to address fundamental issues critical to the development of an efficient and robust capability to understand, analyze, and predict combustion instabilities in contemporary and future rocket engines [23]. Reduced-basis models are proposed and trained by high-fidelity models. The developed tool can provide effective and efficient assessment of the combustion stability behaviors of a practical system with complex geometry over a broad range of operating conditions.

3. Plasma Assisted Combustion

The goal of this project is to establish a comprehensive computational and theoretical framework capable of predicting the impact of nonequilibrium plasmas on ignition and combustion of hydrogen and hydrocarbon fuels in a broad range of temperature, pressure and flow conditions. The numerical results have shown close agreement with available experimental data [24].

4. Nano-Energetic Materials

This research involves development and characterization of smart functional nano-energetic materials for next-generation propulsion and energy-conversion applications. A theoretical and numerical framework has been established to perform high-fidelity simulations that span a wide range of scales, from atomistic to meso- and macro- scales [25].

D. Active Research Experiments

1. Combustion Dynamics

Current experiments focused on combustion dynamics take a number of forms, and can be classified as either self-excited or externally excited. Self-excited experiments are designed around a combustor that is naturally thermoacoustically unstable, while externally excited experiments use speakers (in atmospheric pressure environments) or forcing sirens (in pressurized environments) to impose an acoustic excitation. These experiments usually aim to study the flow/flame response leg of the combustion instability phenomenon, which often entails high speed PIV and PLIF measurements, which are used to either develop flame transferal functions, support simulations and/or hydrodynamic stability analyses, and/or extract deeper physical understanding of the phenomenon. Currently, these types of experiments are conducted in a range of different types of combustors, ranging from bluff body configurations to single or multi-nozzle swirler arrangements, from gaseous fuels to liquid fuels, and from atmospheric pressure to elevated pressure.

2. Forced Ignition

Work is also being performed in the laboratory to improve the reliability of combustion systems, especially when operating at high performance and fuel efficient conditions, through understanding the influential physics of forced ignition in flowing combustors. This physical sensitivity is of interest to the combustion community and industry partners as devices perform closer to their operability limits and need to ignite or re-ignite with high probability. This investigation has taken advantage of the fuel and air supply capabilities of the laboratory as well as the advanced diagnostic techniques available. High speed schlieren has been performed to visualize the boundary of the evolving ignition kernel in the flowing combustor and CH and OH PLIF diagnostics have been used to characterize the combustion chemistry evolution. This work has characterized the influence of flow variables on the forced ignition problem and continues to investigate the role of fuel properties in the process.

3. Laminar Flame Speed – Fuel Characteristics

Laminar flame speed (S_L) measurements are primarily used to study flame propagation and validation of chemical kinetic models. The laboratory is equipped to carry out two different kinds of S_L measurements, the Bunsen flame technique (BFT) and the stagnation flame technique (SFT). BFT provides a simple way to measure un-stretched S_L and is used to measure flame speed at several conditions relevant to ground based and aircraft combustors. Whereas SFT is generally used to validate BFT results when required, this technique is complex and involves stretch corrections to arrive at un-stretched S_L values. The capabilities of experimental setup include for variation of preheat temperatures (300 K - 700 K), pressures (1 atm - 10 atm), equivalence ratio (0.4 - 2), fuels and oxidizer composition (i.e. vitiation) [7– 9]. Several different fuels have been tested, these include syngas, natural gas, liquid jet fuels and alternate fuels. Current research work includes investigation of the role played by alkenes in the reaction chemistry of heavy hydrocarbon fuels. The SFT is shown in Fig. 6.

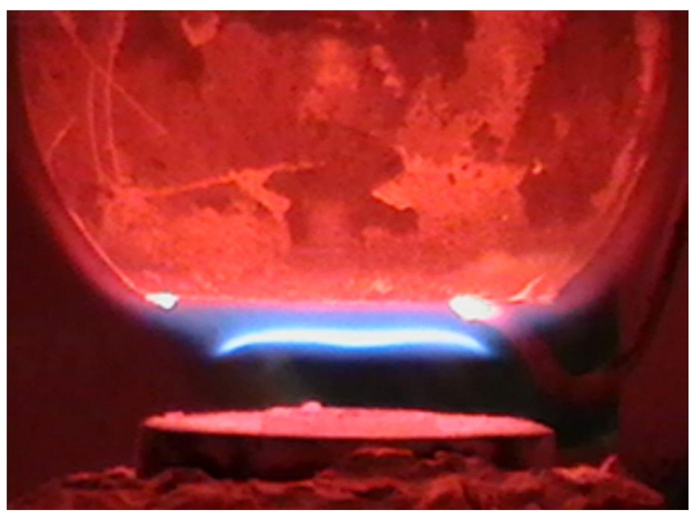

Figure 6. CH_4:C_2H_6 (60:40) – air stagnation flame at 650 K, 5 atm (Φ=1.0)

4. Shocktube

High pressure shocktube enables researchers to study combustion kinetics and better understand the efficiency and carbon emissions of next generation gas turbines. This recent addition to the Combustion Lab is made of stainless steel and weighs up to 8 tons making it structurally sound to replicate extreme engine conditions characterized by high pressures and temperatures. Combustion chemistry studies conducted in the shocktube are supported by advanced laser absorption spectroscopy to understand how different fuels are oxidized in engine environments. The Georgia Tech shocktube is certified to operate at pressures up to 375 atm with temperatures in the range of 800 K to 2500 K. The shocktube has 6 inch inner diameter and 8 inch outer diameter with 69 ft total length. The system also comes outfitted with multiple optical windows. The new testing system, pictured in Fig. 7, is one of the largest high pressure shocktubes in the world for combustion kinetic study.

Figure 7. The 69 ft shocktube at Georgia Tech

5. Premixed Flame Kernel at Extreme Conditions

Compressible flow environments in state-of-the-art gas turbines and high-speed propulsion systems require a deep understanding of the interaction between turbulence and reacting flows to ensure reliable designs and simulation results. Thus, in a range of subsonic and supersonic experiments the behavior of premixed flames under the influence of high turbulence intensities, dilatation effects and hydrodynamic instabilities on reactions rates and flame surface dynamics is investigated [10 – 11]. Mean flow velocities range from Mach 0.1 to Mach 2 and turbulence intensities can be up to 20% of the mean flow velocity using an active vain grid. Results obtained from the experiments are augmented with DNS and LES studies to develop and test scalings and closures for computational models. One of the main goals in the current experiments is the removal of mean strain effects (related to flame anchoring) on the flame development. Therefore, freely propagating flame kernels in a methane-air mixture are generated using a laser ignition system.

The background turbulence and flowfield is characterized both using hot-wire and PIV. The flames are probed using qualitative OH-PLIF and Schlieren imaging from which flame surface properties and flame speeds can be derived. PIV imaging in the reacting case augments these results with information about gas expansion effects, changes in the turbulent properties due to heat release and effects of compression and expansion waves. Recently information about the reacting flow temperature field has been extracted using a Filtered Rayleigh-System. With sufficient resolution and combined with PIV, such results can be used to calculate the turbulent velocity-temperature correlation and assess the validity of LES closures.

6. Spray Physics and Engine Research Laboratory

The SPhERe Lab conducts fundamental combustion and spray research to enable improved combustion efficiency and reductions of pollutant emissions in direct-injection gasoline, diesel and alternative fuel engines. One main goal of the SPhERe Lab is to execute work in a unique tightly-coupled experimental and model-based approach, integrating projects that apply advanced laser diagnostics to probe in-cylinder mixing and combustion processes with projects that utilize these measurements to validate and improve engine CFD models. Using this coupled experimental/computational approach the discovery of unknown spray and combustion physics can be accelerated, as well as the development of robust computational design tools which can be used to optimize engines for low emission high-efficiency performance. The Spray Physics and Engine Research lab employs a continuous flow constant volume optically accessible combustion chamber that can reach up to 100 bar and 900 K to simulate engine-like conditions. It is equipped with a fuel-flexible fuel system that can accommodate a wide range of direct injection diesel or gasoline injectors.

Current work includes the development a joint visible and x-ray extinction measurement technique to quantify axial and radial distributions of the path-integrated Sauter Mean Diameter (SMD) along the periphery of the spray for a range of diesel-like conditions. The SPhERe lab employed Diffused Back Illumination, while Argonne National Laboratory used x-ray radiography. Taking a ratio of these two measurements while applying Mie-scatter equations allows for an extraction of the SMD. This project aims to better understand the complicated multi-phase and multi-scale physics of spray atomization. Also, the SPhERe Lab is pursuing an experimental and computational study of Ducted Fuel Injection to reduce soot particulate matter in engine out emissions. The goal is to understand the fundamental physics driving this phenomenon by studying a range of duct geometries both experimentally and computationally. To probe the spray and combustion physics we employ high speed Schlieren and luminosity imaging to extract lift off length, ignition delay, vapor penetration rate, and soot luminosity [13].

7. Turbulent Flame Speed

Turbulent flame speed measurements have significant influence on essentially all important combustor operational and emissions metrics, including ignition, blow off, and combustion instability. Moreover, the ability of models to capture operational limits such as blow off and ignition in the highly unsteady flows encountered in combustors generally require advanced approaches, such as LES. LES models often use flame let approaches that require turbulent flame speed closures. The facility at Georgia Tech measures the turbulent flame speed of gaseous 4 component fuels at nozzle velocities up to 70 m/s and pressures up to 20 bar. These measurements are used to validate computational models such as LES to better understand turbulent flame speed effects on modern gas turbine engines.

III. HPEPL Facilities

HPEPL is co-located with the Structural Engineering and Materials Laboratory, shown in Fig. 8, at NARA at the Georgia Institute of Technology. HPEPL offers more than 4,000 ft^2 of total test area for industry-scale EP thruster performance test operations. The laboratory's ample workspace can further accommodate custom test configurations and additional equipment [26].

Figure 8. HPEPL Test Facility at the Structural Engineering and Materials Laboratory

A. Vacuum Test Facility 1

Vacuum Test Facility 1 (VTF-1), pictured in Fig. 9, is a diffusion-pumped vacuum chamber capable of reaching base pressures as low as 1 x 10^{-5} Torr. Two 3800 cubit-foot per minute (CFM) blowers and two 495 CFM rotary-vane pumps evacuate the chamber to moderate vacuum (30 – 100 mTorr) before six NRC/Varian HS48-95,000 fractionating diffusion pumps with copper baffles chilled by three Polycold fast cycle water vapor cryopumps bring the chamber to high vacuum. The diffusion pumps have a combined pumping speed of 600,000 l/s on air, 840,000 l/s on hydrogen, and 155,000 l/s on xenon [27]. VTF-1 is additionally equipped with a turbomolecular pump system that allows for testing of chemically active propellants not normally compatible with diffusion pump operation. The system consists of one Edwards STP-XA3203 turbomolecular pump capable of pumping 3,200 l/s on air backed by a 64.6 CFM Edwards GV80 dry scroll pump. Pressures inside the chamber are recorded by an externally mounted Agilent BA 571 hot filament ionization gauge.

Figure 9. Vacuum Test Facility 1 (VTF-1)

Measuring 7 meters in length and 4 meters in diameter and structurally capable of housing two tons of equipment, VTF-1 is suitable for a wide variety of EP testing applications. Plasma diagnostic probes can be situated on linear or rotary tables and swept throughout the chamber in a variety of configurations. Thrust measurements can be made with a NASA Glenn Research Center null-type inverted-pendulum thrust stand cooled by a VWR Polyscience 1173-P recirculating chiller [28]. All testing is monitored and controlled by human operators inside Control Room 1 (CR-1), which houses a variety of power supplies, data acquisition systems, mass flow controllers, ion gauge controllers, and computers.

A gas supply storage area located outside of the lab building comprises of two ventilated bottle enclosures and allows for testing with flammable and toxic gasses. The flammable gas enclosure has a capacity of 1800 ft^3 and the toxic gas enclosure has a capacity of 300 ft^3. Gases stored in the exterior storage area are fed into the chamber via a stainless steel ATEX-rated enclosure, which is continuously purged with low-pressure nitrogen flow. This allows VTF-1 to accommodate a wide variety of propellants such as hydrogen and ammonia which may be needed to simulate unique operating conditions for analysis.

B. Vacuum Test Facility 2

Vacuum Test Facility 2 (VTF-2), pictured in Fig. 10, is a cryogenically-pumped vacuum chamber measuring 9.2 meters long and 4.9 meters in diameter. The test chamber uses a circular entry door 2.1 meters in diameter. The test facility employs one 3800 CFM blower and one 495 CFM rotary-vane pump for rough-pumping and bring the internal pressure down to about 30 mTorr [29, 30].

Figure 10. Vacuum Test Facility 2 (VTF-2)

To generate high-vacuum conditions, VTF-2 utilizes 10 CVI TM-1200i cryopumps installed inside the chamber at the aft and fore sections. During nominal operating conditions, the cryopumps can generate a nominal pumping speed of 600,000 l/s on air and 350,000 l/s on xenon [30]. The cryopumps are connected in parallel and supplied by a Stirling Cryogenics SPC-8 RL closed-loop recirculating liquid nitrogen (LN2) feed system. The two-phase recirculating system employs two SPC-4 cryogenerators to reliquify gaseous nitrogen and store inside a 1,500 liter LN2 reservoir. The cryosystem is responsible for cooling down 10 CVI TM-1200i cryopumps and allowing the chamber to reach base pressures as low as 1.9×10^{-9} Torr [30].

The chamber offers an elevated platform capable of supporting a load of 2 tons. As part of the platform is the test article structure equipped with an EP device interface plate, a null-type inverted-pendulum thrust stand, and an electronics thermal control system. Additionally, the test article section has multiple power and telemetry cable connections that feed through VTF-2's various chamber penetrations. Each chamber penetration can be modified to accommodate power connections, data acquisition cables, and propellant flow lines. The one meter wide frame allows researchers to test EP devices in a variety of configurations and further facilitates thruster installation. Lastly, the test article structure comes equipped with a motion control system that can perform radial sweeps across the thruster exit plane for plasma diagnostics. The VTF-2 test article structure is shown in Fig.11. VTF-2 offers the full range of plasma diagnostics for a variety of test conditions. Plasma diagnostic probes are mounted on to plate fixtures which are actuated by linear and radial motion mechanisms and controller at various speeds by personnel. The linear motion tracks can be installed at different locations alongside the test article structure to meet specific experiment objectives.

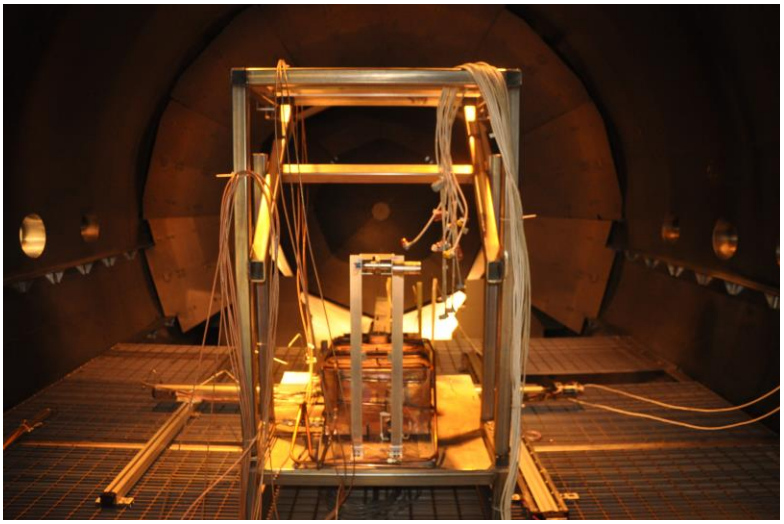

Figure 11. Test Article Structure in VTF-2

The VTF-2 aft section uses a conical structure covered in graphite paneling to help reduce sputtering from the high-energy ions generated by EP thrusters during operation. The conical shape helps reduce perpendicular reflection of ions bombarding the graphite surface and further mitigates backpressure effects near the test article section. Behind the conical beam dump section, as seen in Fig. 12, is a single-phase thermal control system designed to dissipate excess heat generated by long period test operations. The beam dump cooling system utilizes the air-cooled Julabo FL7006 chiller to remove up to 7 kW of heat at 20 C [31]. This recent upgrade enables VTF-2 to perform rigorous tests on high-power EP thrust devices for longer periods of time.

Similar to VTF-1, all test operations are monitored and commanded from inside control room 2 (CR-2). As previously mentioned, CR-2 also comes outfitted with power supplies, a mass flow control system, ion gauge controllers, and data acquisition suite. Depending on the test requirements, CR-2 can be modified to meet customer needs. In-house calibration techniques have been developed to capture error for experimentally obtained quantities such as mass flow rates values, thrust, and plasma potential.

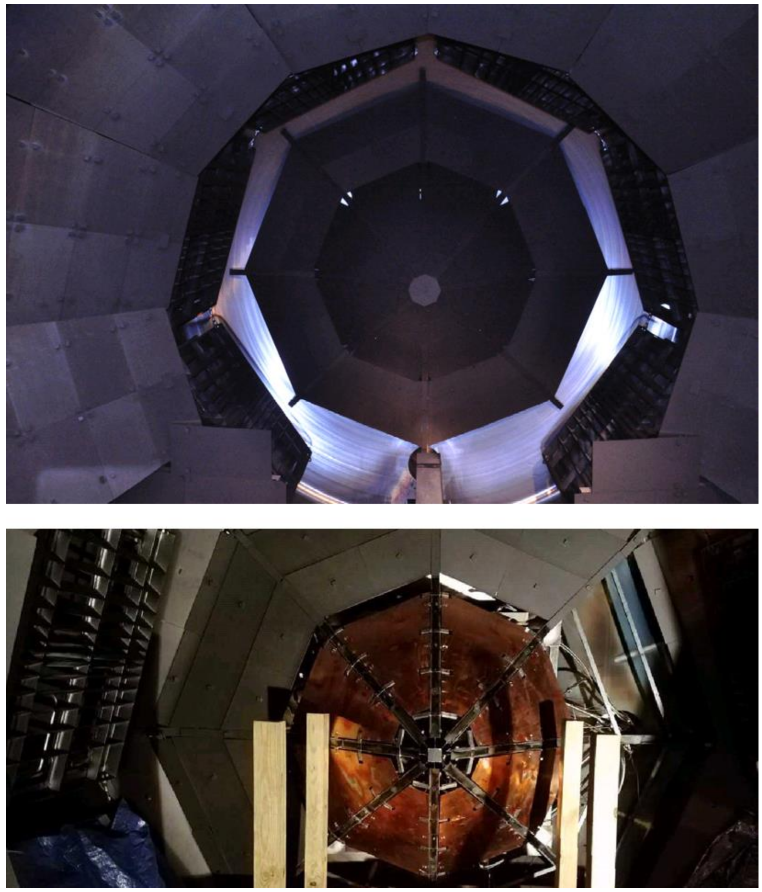

Figure 12. Graphite conical beam dump and cooling system insideVTF-2

C. Plasma Diagnostic Probes

HPEPL employs many of the standard plasma diagnostic probes utilized to investigate the plumes of EP devices. These include emissive, Langmuir, Faraday, retarding potential analyzer (RPA), and ExB probes, as well as a high-speed axial reciprocating probe (HARP) that enables rapid insertion and removal of probes for internal thruster diagnostics. A summary of the capabilities and operation of each probe is included here, and the reader is referred to the literature for more detailed descriptions of probe theory and operation.

Emissive probes provide a measurement of the local plasma potential; a tungsten filament positioned in the plume is heated by current from a power supply until the filament thermionically emits enough electron current to neutralize the sheath formed around the probe. The resulting floating potential of the probe is the local plasma potential [32]. Cylindrical Langmuir probes consist of a conducting wire that is biased across a range of voltages. The resulting I-V trace can be analyzed to determine the plasma density, electron temperature, floating potential, and plasma potential [33].

HPEPL houses two JPL-style nude Faraday probes, each consisting of a tungsten spray-coated aluminum collector electrode and stainless steel annular guard. The guard and collector are biased to the same voltage to ensure the formation an approximately uniform sheath over the collector. The probe is typically swept about the thruster plume in a constant angle arc and the resulting current trace can be analyzed to provide ion current density and plume divergence measurements [34].

Figure 13. HPEPL ExB Probe

RPA probes measure ion energy distribution by selectively filtering ions with a series of biased grids. HPEPL owns three RPA probes, each with varying levels of grid transparency. All probes consist of a collector electrode and four grids: floating, electron repulsion, ion repulsion, and secondary electron suppression. The floating grid acts to reduce perturbations between the probe and plasma, the electron repulsion grid impedes collection of plasma electron current, the ion repulsion grid is swept through a range of voltage biases to selectively filter ions based on ion energy, and the electron suppression grid mitigates the collection of secondary electrons generated by ion collisions [35].

HPEPL's ExB probe, show in Fig. 13, enables determination of ion charge population. The ExB probe generates uniform electric and magnetic fields that are perpendicular to each other and to ion velocity. Speed of the ions traveling through the crossed fields to the collector is directly related to field strength and ion charge; thus, by varying the magnitude of the electric field, ions can be selectively filtered by charge [36].

D. Laser Diagnostics

Though physical plasma probes have considerable heritage in the EP community, such probes can perturb the plasma and are therefore inherently invasive [37]. HPEPL is developing the capability to perform non-invasive optical plasma diagnostics with two distinct methods: Thompson scattering and terahertz time-domain spectroscopy (THz-TDS). HPEPL's Thompson scattering system will employ scattering of electromagnetic radiation by free electrons in plasma to provide time-averaged measurements of electron temperature and number density at spatial resolutions under 500 µm. The system will feature a Continuum Powerlite 8000 frequency doubled 532 nm Nd:YAG laser that will provide pulses at a rate of 10 Hz into the plasma. Light scattered by the laser pulses will be filtered and dispersed by a spectrograph, and the resulting spectrum will be captured by a CCD camera [38-41].

HPEPL will provide the first ever THz-TDS measurements of an EP device. Two mode-locked Coherent Vitara-T-HP femtosecond 800 nm Ti:sapphire lasers will be frequency offset to produce scanning rates on the order of 1 to 10 kHz as part of a high-speed asynchronous optical sampling (ASOPS) system [42]. The two lasers will pump and probe GaAs photoconductive (PC) antennas to generate and measure THz waves, respectively. Shifts in THz phase caused by the presence of free electrons in the plasma will yield time resolved line integrated electron number density measurements at frequencies equal to the scanning rate [43-45]. With the ability to resolve changes in electron number density at high frequencies, HPEPL will be able to provide new insights into the mechanics of electron mobility in EP devices. Initial THz-TDS setup efforts are pictured in Fig. 14.

Figure 14. THz-TDS Initial Setup Efforts

IV. Research Collaboration Partners

Premier government agencies, such as the AFOSR, Air Force Research Laboratory (AFRL), Federal Aviation Administration (FAA), and the Defense Advanced Research Projects Agency (DARPA), as well as industry organizations like Spectral Energies LLC, have and continue to collaborate with these Georgia Tech research laboratories. From such collaborations, many notable contributions have resulted adding to the experience and technical prowess of each P&C research laboratory.

A. Combustion Laboratory

The laboratory has developed strong partnerships with government and industry, serving as a formal center of excellence for several global energy and propulsion companies. A core guiding philosophy of the types of projects worked on the laboratory is "doing fundamentals at realistic conditions" - i.e., to perform theory, do experiments, and develop diagnostics that are directed toward practical conditions, such as high pressure, temperature, and Reynolds number.

The Ben T. Zinn Combustion Lab enjoys a highly collaborative approach to research. Recent external collaborations have produced journal publications from partnerships around the globe, including dynamical systems work with researchers from IIT Madras in India, hydrodynamic stability analysis work with researchers from Cambridge University in the UK, cutting-edge optical diagnostic measurements in difficult environments with partners from Spectral Energies, LLC and the AFRL, and many other close collaborations with the other major combustion groups in the US.

Key advances made through these partnerships impacting the field of combustion over the last decades include: 1) application of the Galerkin method for solving combustion instability problems, 2) demonstration of active control of combustion instabilities, 3) prediction and control of limit phenomenon, such as blow off, in combustion systems, 4) advanced, low emissions architectures for combustion systems, and 5) development and application of large scale computations for practical devices.

B. HPEPL

Prof. Walker has established lasting relationships with many stakeholders in the government and industry sectors interested in advancing EP technology. Notable collaboration partners from government are the AFOSR, Office of Naval Research (ONR), DARPA, and NASA. Given Prof. Walker's expertise in high-power EP devices, many industry players have collaborated with HPEPL as well including Lockheed Martin, Boeing, Northrup Grumman, IHI Aerospace, Aerojet Rocketdyne, Blue Canyon, and L3 Electron Technologies.

Under the direction of Prof. Mitchell Walker, HPEPL has become a premier academic laboratory making headway in the EP field and plasma physics. Since its establishment in 2005, HPEPL has impacted the field in three distinct areas: 1) acceleration of plasmas with helicon plasma sources, 2) characterizing the impact of facility effects on the operation of high-power electric propulsion devices called Hall effect thrusters (HETs), and 3) investigation the plasma sheath behavior given the bounding wall material. Students have explored the feasibility of novel thruster concepts, such as helicon ion thrusters and ion focusing HETs; performed fundamental plasma physics research to understand HET power deposition and wall erosion; and expanded upon facility effects literature by developing the field of electrical facility effects and investigating the impact of HET neutral ingestion [27, 29, 37, 46 -50]. HPEPL has additionally assisted in the testing and development of commercial HETs, gridded ion thrusters, and arcjets. Such experience makes HPEPL an obvious choice for many industry clients seeking to test EP devices.

V. Conclusion

The P&C group at Georgia Tech manage a highly-capable research center that can fully support and progress the nation's initiatives that aim to improve the environment, economy, and security domains. The research laboratories come outfitted with essential mechanical equipment, unique experimental facilities, diagnostics, and adept personnel to make meaningful contributions in combustion science, plasma physics, and computational modeling and simulation. The co-location of the P&C research laboratories makes it convenient for external entities to leverage the assortment of competencies offered by the multi-disciplinary teams. Current P&C laboratory directors have facility expansion plans that will strengthen the suite of capabilities for future endeavors. Furthermore, the aerospace engineering department continues to onboard qualified research faculty and seasoned experts to cultivate a world-class academic curriculum and ensure a sustainable knowledgebase in propulsion and combustion sciences.

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