SLATT UNDERGRADUATE RESEARCH FELLOWSHIP
FINAL REPORT

SCHOLAR NAME:	Ryan Bencivengo
FACULTY ADVISOR:	Dr. Sergey Leonov
PROJECT PERIOD:	January – May 2023
PROJECT TITLE:	Optimization of Energy Deposition Pattern for Plasma-Assisted Combustion
CONNECTION TO ONE OR MORE ENERGY-RELATED RESEARCH AREAS (CHECK ALL THAT APPLY):	**(Y) Energy Conversion and Efficiency** **( ) Sustainable and Secure Nuclear** **( ) Smart Storage and Distribution** **( ) Transformation Solar** **( ) Sustainable Bio/Fossil Fuels** **( ) Transformative Wind**

MAJOR GOALS AND ACCOMPLISHMENTS

Summarize your research goals and provide a brief statement of your accomplishments (no more than 1-2 sentences). Indicate whether you were able to accomplish your goals by estimating the percentage completed for each one. Use the next page for your written report.

RESEARCH GOALS	ACTUAL PERFORMANCE AND ACCOMPLISHMENTS	% OF GOAL COMPLETED
Final Construction of High Voltage Power Supply	All relevant circuitry and assembly for the power supply was completed according to the original schematic.	100
Failure Testing for Power Supply	Testing of individual components was performed and necessary changes were made to the placement and setup when necessary.	100
PIM Test using Power Supply	The PIM Test was completed using the SBR-50 wind tunnel at the University of Notre Dame where data for and images of the plasma in supersonic flow. were obtained.	100

RESEARCH OUTPUT

Please provide any output that may have resulted from your research project. You may leave any and all categories blank or check with your faculty advisor if you are unsure how to respond.

CATEGORY	INFORMATION
EXTERNAL PROPOSALS SUBMITTED	N/A
EXTERNAL AWARDS RECEIVED	The AFRL (Dayton) funded Project was extended to 2023. Title “Optimization of Supersonic Combustor Performance Using Selective Energy Deposition through PIM Technique”, total funding $282k
JOURNAL ARTICLES IN PROCESS OR PUBLISHED	AIAA Paper will be submitted to AIAA SciTech Forum 2024, Orlando, FL, January 2024, Abstract submission deadline May 25, 2023; Title “Optimization of Plasma-Injection Module (PIM) Technique Implemented in Supersonic Combustor”, Authors E. Braun, R. Bencivengo, P. Lax, T. Ombrello, S. Leonov. The paper will be submitted to AIAA Propulsion and Power Journal.
BOOKS AND CHAPTERS RELATED TO YOUR RESEARCH	N/A
PUBLIC PRESENTATIONS YOU MADE ABOUT YOUR RESEARCH	N/A
AWARDS OR RECOGNITIONS YOU RECEIVED FOR YOUR RESEARCH PROJECT	N/A
INTERNAL COLLABORATIONS FOSTERED	Mr. Henri Doucet, University of Notre Dame, Graduate Student Mentor, 1-2 times per week. Dr. Sergey Leonov, University of Notre Dame, Research Professor Mentor, 1-2 times per week
EXTERNAL COLLABORATIONS FOSTERED	N/A
WEBSITE(S) FEATURING RESEARCH PROJECT	N/A
OTHER PRODUCTS AND SERVICES (e.g., media reports, databases, software, models, curricula, instruments, education programs, outreach for ND Energy and other groups)	N/A

RESEARCH EXPERIENCE

Please let us know what you thought of your research experience: Did this experience meet your expectations? Were lab personnel helpful and responsive to your needs? What else could have been done to improve your experience or achieve additional results?

Performing research this semester was a great experience. I was able to grow my technical skills through working with cutting edge technology and materials, while also growing my professional skills by working with graduate students and research professors. By being able to work on an incredibly interesting project related to hypersonics and energy, I was able to gain exposure into an exciting field of engineering that I could possibly work in some day.

FINAL WRITTEN REPORT

(Please use the space below to describe your research project and objectives, any findings and results you can share, and graphs, charts, and other visuals to help us understand what you achieved as a result of this research experience.)

Optimization of Energy Deposition Pattern for Plasma-Assisted Combustion

Ryan Bencivengo
AME, University of Notre Dame

Introduction

The general objective of this research project is to study the transient physical and chemical processes associated with plasma-based ignition and flameholding in supersonic flow, which is related to prospective air-breathing hypersonic propulsion systems. This area of research and development is one of the US National Priorities and Defense Department's highest technical modernization priorities (https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf). This goal is within the scope of the ND Energy activity.

The entire research project consists of several technical tasks, one of them is the proper optimization of the energy input for plasma-assisted combustion (energy deposition pattern). This task requires an understanding of the physical processes relevant to plasma-flow coupling and chemical kinetic processes associated with certain ignition phenomena. The power supply response function and the plasma generator geometry control the energy deposition and making it as efficient as possible is key to the success of this process. Specifically, the team is examining the hypothesis for a two-leveled plasma regulation system: high (10kV) voltage for the plasma initiation and a lower (2kV) voltage with a high (>10A) current for the plasma elongation and support.

The particular research tasks relevant to the Slatt fellowship Project, performed in collaboration with Dr. Leonov and graduate student Mr. Henri Doucet (during the 2022 fall semester), consist of the design and construction of the power supply and using this power supply for the supersonic combustion control test campaign. Specifically:

-drafting a design of the high-voltage components arrangement within the power supply rack;

-assembling and testing of both the individual components and an entire assembly;

-adjusting the experimental set-up parameters to diminish secondary effects and excessive heating;

-providing parametric analysis of the testing data, including the waveforms of plasma initiation, and an initial electric field configuration;

-adjusting the waveforms by means of electrical circuitry when deviations from theoretical plasma behavior are found (remaining for 2023 Summer and Fall semesters efforts).

-report compilation and further planning.

Approach and Results

The efficient mixing of fuel and air over short length scales is critical for a supersonic airbreathing engine. At flight Mach numbers between 5 and 8, stagnation temperatures are relatively low producing long ignition delay times in the combustor, longer than the fuel residence time, leading to inefficiency. In this regime, diffusive combustion dominates at low pressure [1] and fuel injection techniques with acceptable stagnation pressure loss and highly efficient near field mixing are favored. The technique based on Quasi-DC electrical discharge and Plasma Injection Module (PIM) system has been previously explored [2] to increase penetration depth, enhance air-fuel mixing and improve the combustion stability limit [3, 2]. PIMs couple a quasi-DC plasma to the fuel injection port and have also been extensively applied for plasma-based ignition and flameholding in supersonic combustors [2]. In previous work, the PIM construction was optimized for use on a metallic grounded wall, as shown in Fig. 1. However, the PIM efficiency, operational characteristics and, particularly, operability under harsh environmental circumstances are limited by a construction of the Power Supply (PS). One more complication for the PS construction is that it should work with several PIM devices, since having multiple PIM devices allows for more effective ignition in the jet. Therefore, the PS should have a multi-channel architecture.

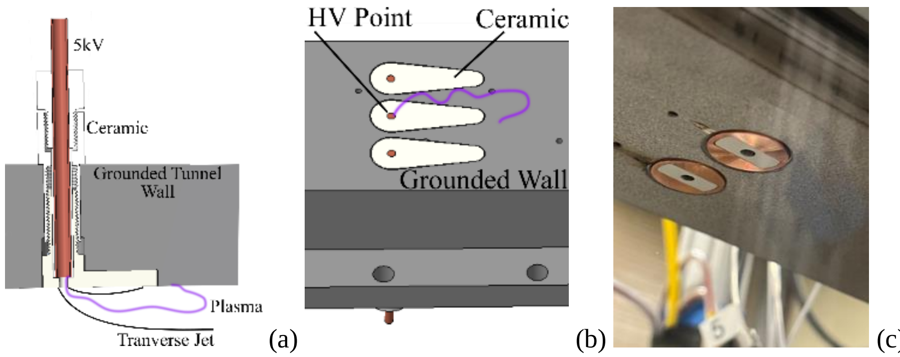

Figure 1. Schematic representation of PIM geometry where (a) shows a centerline cross-section of PIM installation into the combustor wall, (b) shows a distribution of 3 PIMs in the spanwise direction, and (c) photograph of two PIMs installed in supersonic combustor.

Three basic concepts were tested previously to energize the PIMs:

- (1) big capacitor high-voltage (up to 6kV) bank with the power distribution over several channels;
- (2) working current power supply (2kV, 5A) and NS high-frequency generator for initial breakdown/plasma enhancement separated by a passive filter;
- (3) separate breakdown voltage (10kV) power supply and working current power supply (2kV, 5A).

Each of them has some benefits and drawbacks, such as a low efficiency, unstable breakdown at high pressure, EM noise, cost, and problems with operation. For the current project, four-channel system, we considered one distinct architecture shown schematically in Fig.2a. It is represented by one DC breakdown (10kV) box and four DC main current boxes (2kV, 5A), – this system was assembled, tested, and exploited during this semester.

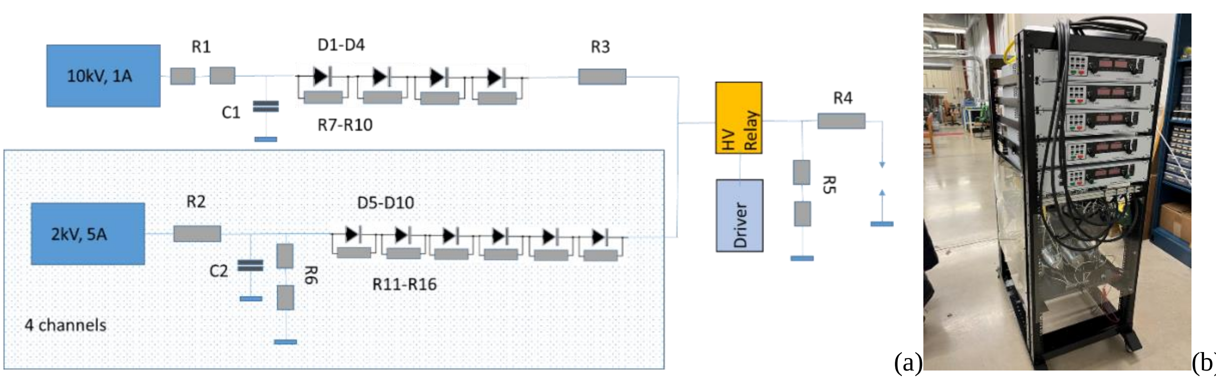

Figure 2. Double DC architecture presented for a single channel (four 2kV boxes for 4 channels system). (a) – schematics; (b) – PS assembled photograph at White Field Laboratory.

The diagram below indicates the project's performance timeline which included the PS assembling, PS initial shakedown in terms of possible failures, testing at model loads, and testing with PIM installed in supersonic combustor. As a note, much of the initial assembly was completed during the 2022 Fall Semester.

Task	January 2023	February 2023	March 2023	April 2023
Final assembly				
Failure test				
Model test				
PIM test				

Figure 3 below shows some details of the construction and initial testing of the PS. It indicates some important components tested separately before and after the assembling.

Figure 3. Major components and failure testing result: (a) - Close up of PS components during initial assembly and wiring (b) – back side of the PS at wiring; (c) – side view of the PS with major components; (d) - failure test, all boxes in operation, #1, #2 and #4 are loaded; (e) – three PIMs before wind tunnel installation.

For the assembly of the power supply, the placement of the required circuitry components was measured and planned out ahead with prevention of excessive heating and ease of wiring as the main goals. These components were then attached to the board using screws or adhesive. Devices to hold the high voltage relays in place, while also allowing access to the terminals, were designed in CAD software, 3D-printed, and attached to the plastic board with screws, as can be seen in Fig. 3a.

The PSs tests with PIMs were performed at the SBR-50 wind tunnel at the University of Notre Dame with a Mach number of 2. The facility is a direct-connect blowdown test rig with a steady-state run time of t ~0.7s in the current configuration. The test geometry models a 2-D plane-wall supersonic combustor with a 1° expansion of the top and bottom walls to accommodate boundary layer growth and suppress thermal choking at combustion. An overview of the test geometry is shown in Fig. 4. The initial cross-section at the nozzle exit is Z×Y = 76.2mm × 76.2mm and the total length from this point to the diffuser is X = 800mm. The plenum temperature can be varied through electrical preheating, and for this testing was adjusted from T_0 = 297-500K with stagnation pressures from P_0 = 1-3bar. Optical access into the test geometry is provided by quartz windows on the side walls and a fused silica port in the vacuum tank. Forty-eight pressure ports are distributed evenly across the top and bottom walls and a 16-

channel pitot rake was installed at the downstream end of the test section along the test section centerline (Z = 0mm) and distributed in the Y direction.

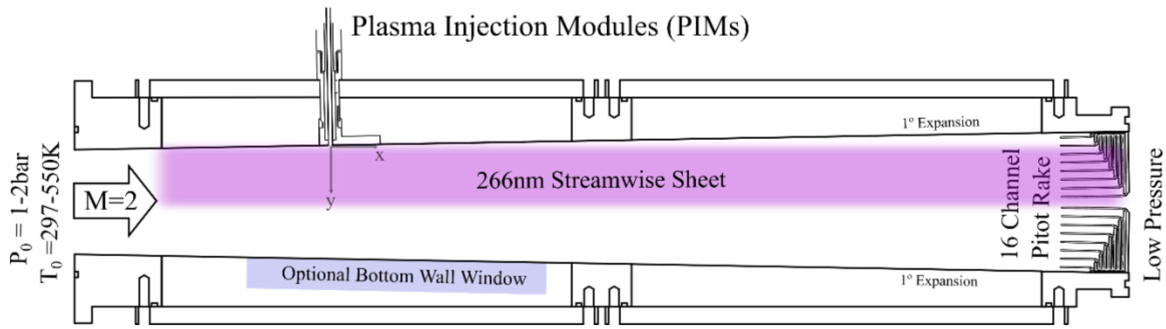

Figure 4. Schematic of the test section with the location of the PIMs and the streamwise laser sheet for Acetone PLIF visualization.

Ethylene (C_2H_4) injection through the PIMs was used in this study. Figure 4 also indicates the laser sheet arrangement to perform Acetone PLIF visualization, which is planned to complement the existing dataset. The dataset includes the high-speed imaging and the electrical probe measurements. High-speed imaging was acquired with a Photron FastCam Nova S9 at 50kHz with typical exposure time 4μs. The discharge dynamics are dictated by the flow-plasma coupling phenomena.

In the current test series, two basic modes of the discharge behavior were observed: (1) a continuous discharge connection to the downstream ring with the discharge location in the boundary layer, as it is shown in Fig. 5a; and (2) the elongated form of the discharge when it is frozen to the fuel jet, as it is shown in Fig. 5b. The discharge mode transition from a short pattern to the elongated one, which is the target, is controlled by two factors: the fuel mass flow rate and the parameters of the newly assembled power supply. In the current geometry, the elongated form was created at a fuel mass flow rate in a range of $\dot{m}$=2-5g/s. At lower rates of fuel injection, the plasma behavior demonstrates a short pattern.

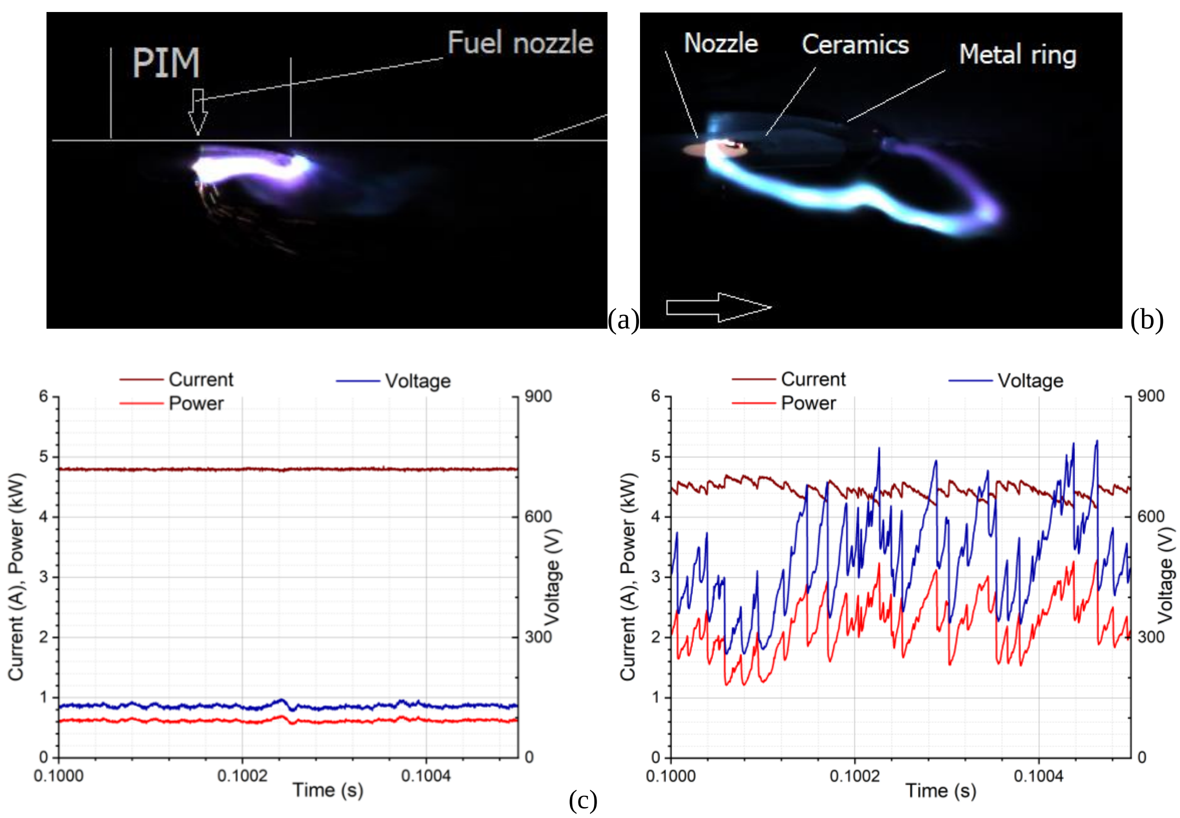

Figure 5. PIM operation under control of newly assembled PS: (a) short connection; (b) extended form of plasma filament; (c) –typical oscillogram of electrical parameters at short connection; (d) – in oscillating mode.

The electrical measurements, in general, support the high-speed camera records, see Fig. 5c and 5d. For a short connected electrical discharge, Fig. 5c, which is realized at low fuel mass flow rate or at air-to-air injection, the discharge voltage and power are relatively low: the electrical power is deposited in electrode areas the most. For the elongated discharge, Fig. 5d, the discharge voltage has a saw-tooth waveform indicating the phases of the discharge length increase with reconnection to a shorted pathway with the abrupt voltage decrease. The voltage magnitude depends on the discharge current (current increase leads to the voltage decrease) by the way that the discharge power occurs to be the most conservative, being about W=2kW in the oscillating mode.

Summary

This work is related to the optimization of the Plasma-Injection Modules (PIM) technique implemented for fuel ignition and flame stabilization is a supersonic combustor. A new, improved, version of the Power Supply was constructed to have a technically reasonable configuration for usage in a wide range of geometries and electrical parameters at multichannel operation. The visualization and electrical probes measurements indicated that this design allows proper operation (the criteria particularly include the elongated form of the plasma filament generated) at wide range of major characteristics such as the applied voltage/current and the fuel mass flow rate.

In summary, all technical tasks planned for the project supported by the Slatt Fellowship Program were successfully completed.

Upcoming work and analysis will be focused on characterizing the different operational modes of the power supply and PIMs and proper adjustment of the parameters of the PS's major components.

Acknowledgments. I would like to thank the Slatt Fellowship Program for their support, and also to the U.S. Air Force Research Laboratory, Innovative Scientific Solutions, Inc. for their financial support of the entire high-speed combustion activity.

References

[1] Q. Liu, D. Baccarella and T. Lee, "Review of combustion stabilization for hypersonic airbreathing propulsion," *Progress in Aerospace Sciences,* vol. 119, p. 100636, November 2020.

[2] S. Elliott, P. Lax, C. C. Sergey Leonov and T. Ombrello, "Acetone PLIF visualization of the fuel distribution at plasma-enhanced supersonic combustion," *Experimental Thermal and Fluid Science,* vol. 136, p. 110668, 2022.

[3] S. B. Leonov, S. Elliott, C. Carter, A. Houpt, P. Lax and T. Ombrello, "Modes of plasma-stabilized combustion in cavity-based M = 2 configuration," *Experimental Thermal and Fluid Science,* vol. 124, p. 110355, 2021.