THE IMPACT OF LEAN DIRECT INJECTION GEOMETRIC PARAMETERS ON LEAN BLOWOUT

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Abstract. The aerospace industry is faced with the challenge of improving modern aircraft engine performance while reducing fuel consumption and emissions. Lean Direct Injection (LDI) offers a cleaner combustion alternative but is prone to lean blowout (LBO), a phenomenon in which engine flames blow out during flight due to insufficient fuel-to-air ratios. This project aims to investigate how engine geometric parameters in an LDI combustion model affect LBO. Studies have demonstrated that swirlers are critical components of LDI and influence flame stabilization. However, limited research exists on the effects of accompanying venturis, and how their geometries affect flow fields and spray characteristics in LDI combustion. Existing research on biconic and parabolic venturis sheds light on flow field variations, but other geometric parameters remain unexplored. Varying venturi geometry may yield insights like those from previous swirler and venturi studies, advancing LDI innovation by exposing lean blowout conditions. Originally, the scope of this project was to analyze varying flow fields via PIV instrumentation. However, hardware failure called for the re-design of the group's LDI combustor. This paper details the efforts made towards the re-design of a fully functional LDI combustion chamber, corresponding operator code, and computational models that represent the system's parameters.

Project Objective. The push from aerospace industries for increased engine performance via reduced fuel consumption and legislation to reduce aircraft emission levels has left innovators with a challenge [1-5,8]. Modern aircraft engines are incapable of meeting the rising demand for ultra-efficient flights that reduce NOx by 75% in accordance with ERA standards [5,8]. Fundamentally, increasing temperature and pressure within the combustion chamber of an engine leads to reduced fuel consumption thereby increasing engine performance [2,3]. However, increased temperature leads to increased NOx emissions [1-3]. In contrast, decreasing the peak temperature of high temperature regions within the flow field decreases the amount of NOx emissions [2,3], but increases the chance of blowout [6]. Lean Direct Injection (LDI) is a reduced-NOx combustion configuration, proposed by NASA [2], with potential to meet demand for cleaner, more efficient engines [5]. However, LDI is prone to lean blowout (LBO), due to its fuel-lean combustion design [6]. The objective of this project is to investigate the impact of LDI geometric parameters on LBO.

Initial Motivations. The initial concepts for LDI combustion were developed through the collaboration of NASA Glenn Research Center and the Department of Energy over four decades ago [2]. Proposed with the ability to minimize NOx through fuel-lean combustion and a reduced flame temperature [1-5], the development of the LDI system was a step towards cleaner, more efficient aircraft engines. With increasing emission concerns [8], industry will need to implement fuel-lean combustion in future engines. The lack of a comprehensive understanding around LBO is a factor preventing the conversion to lean combustion [6]. One such LDI design is the first generation single-point swirler venturi configuration (SV-LDI-1) in which research has been conducted on the swirlers and fuel injectors [1-3]. However, there is still a lack of information on the effects of alternative venturi geometries on LBO.

Swirlers are crucial elements of LDI and have proven to shorten and stabilize the flame through spray dynamic processes including: Rapid vaporization, atomization, and mixing [1-5]. Swirlers create recirculation zones that promote air and fuel mixing [1,3] by mixing combustion products with fuel that did not burn as it initially passed through the base of the flame [3]. These recirculation zones create partially reversed flow fields [3] that shorten and stabilize the flame [1,2]. Experimentation has demonstrated swirl blade angle affects the fuel spray angle, swirl number, and recirculation zones while blade thickness has a limited effect [1-3].

Additionally, similar experimentation has yielded that injector location in relation to the mouth of the venturi is impactful to spray conditions [1]. Further research has determined the impact that converging-diverging and converging-only venturis have on the flow fields [7]. This series of experiments proved certain elements of SV-LDI are directly responsible for lean blowout conditions and spray conditions [1-5].

However, there is a lack of knowledge known about the impact various converging-diverging venturi geometries have on the flow field and, in turn, the spray characteristics in LDI combustion. There have been few investigations on the effects from changing venturi geometric parameters when compared to the work done on swirlers. Dr. Yogesh Aradhey, previous member of Dr. Meadow's research group and former mentor, investigated the effects biconic and parabolic venturis have on the swirl number under cold flow conditions. The data shown in Figure 1 demonstrates the variation in flow field characteristics between the biconic venturi, parabolic venturi, and the venturi designed by NASA.

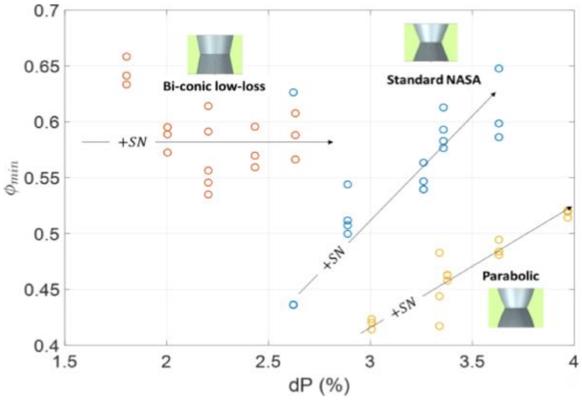

Figure 1. LBO ER limit vs Percent Pressure Drop with SN Trends Included collected by Aradhey and team.

Dr. Aradhey's research does not encompass the effects of other geometric parameters of the venturi including mouth diameter, throat diameter, and divergence angle, aspects which are displayed in Figure 2.

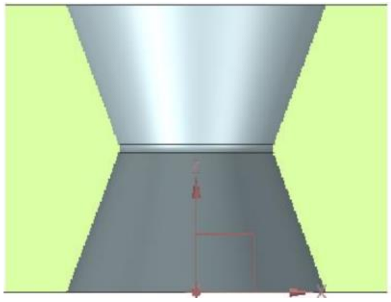

Figure 2. NASA venturi in 2D rending

Varying the geometry of the venturi may lead to findings like those discovered by Dr. Aradhey, and those presented in swirler or injector literature. Determining the impact of venturi geometry on aspects of the flow field and spray characteristics will progress LDI innovation by deepening the understanding of lean blowout conditions.

<u>LDI-DRS Experimental Hardware</u>. The Combustion Laboratory at Virginia Tech accommodates the LDI venturi research project. The lab is outfitted with a testing room containing a modular SV-LDI-1 combustion rig capable of housing the various venturi models. The rig also accommodates the group's direct rotation swirler (DRS) for further evaluation. The group's DRS system was installed onto the rig for venturi and swirler testing. The DRS is capable of rotating swirlers up to 5000 rpm and maintain flame stability in the flame tube. A schematic for the rig with the DRS attachment is shown in Figure 3. The testing room can accommodate a 2D and 3D PIV testing setup. The building has access to a regulated compressor capable of safely reaching pressures of 140 psi and up to par exhaust vents.

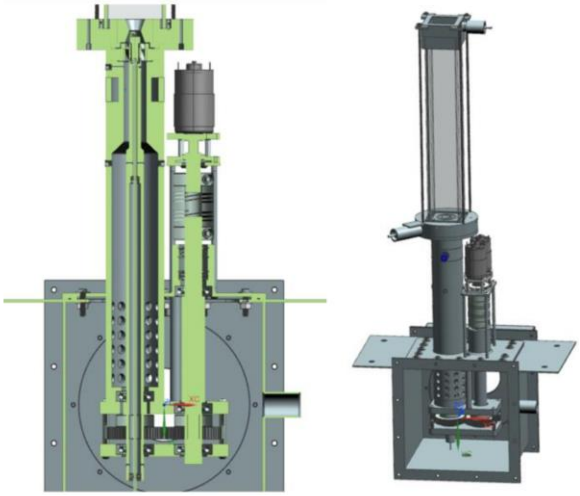

Figure 3. Cross section and 3D model of the combustion testing apparatus with DRS included.

Milestone One: LabVIEW Operator Code.

Previous Operator Code. The development of the previous LabVIEW operator code's interface dates to over 4 years ago, with at least 24 revisions being made to the code since then. These permutations were made as the principle investigations concerning LDI combustion technology changed. Thus, so did the LDI combustion testing apparatus. However, rather than receive a complete overhaul with each alteration in research objective, the LabVIEW operator code was simply revised, causing the interface to become cluttered and overly complex, as displayed in Figure A.1. Furthermore, the code was expanded on, up until the current project, by multiple students that participated in the various LDI research projects involving the modular LDI testing apparatus.

After years of permutations, there was little organization in the previous LabVIEW operator code interface, i.e. the terminal view. There were controls throughout the interface with many of their respective indicators scattered throughout the terminal view. The layout of the controls and indicators lacked any general trend to it, making the code difficult for an uninformed operator to control or monitor the system. Furthermore, many of the interactable controls had unclear labeling and inconsistent notations. The labeling may had been appropriate for the designer, but as an independent researcher unfamiliar with the notation, many of the controls and indicators had to be traced in the LabVIEW block diagram to determine their function and if they were needed for the current project. This process proved to be time intensive for an individual lacking LabVIEW experience, and it even proved challenging for students with over five years of experience as they had to discern the unnecessary clutter and poor notation in the block diagram.

Additionally, many of the features present, including pilot controls, sonic nozzle indicators, and indicators disconnected within the outdated block diagram, were not necessary for the testing required for this research project. The discussed elements all supported the idea to re-design the LDI-DRS operator code.

Revised Operator Code. There were a multitude of reasons that the research group elected to conduct a complete overhaul of the LabVIEW operator code for the purposes of this research project's testing campaign. Most importantly, the PI requested that the operator code block diagram have reduced design complexity and a more robust interface. These two elements successfully assisted in building a strong foundation in

LabVIEW's basic operations. Learning these fundamentals was important as multiple of the group's testing apparatuses operate via LabVIEW codes. It is possible that future undergraduate researchers that operate the LDI-DRS testing apparatus will also have minimal LabVIEW experience, meaning it is imperative that the interface and code structure be intuitive to use and modify.

Another reason that the operator code required a complete overhaul is because the internal design of the previous code had features no longer operational, but due to the complex nature of the design, a comprehensive breakdown of all the code's features would have been far too time consuming to execute. Furthermore, there was an added layer of complexity trying to comprehend the rationale of the previous designers considering there had been multiple students of various LabVIEW experience levels that worked on the code.

Multiple of Dr. Meadow's projects operate via LabVIEW control systems. Therefore, one goal of the redesigned LDI-DRS operator code was for it to be developed in the likeness of the LabVIEW interface used for testing the research group's Navy sponsored testing apparatus, also known as the NAVY rig. However, the NAVY rig is a much larger, more complex gas turbine engine combustion chamber model.

While not as complex, the newly developed LDI-DRS operator code incorporated features that the old code did not. The terminal view maintained a consistent trend, flowing left-to-right with the main controls grouped together in the upper-left corner of the interface. Like the Navy rig operator code, there is a clear schematic of the rig with arrows denoting paths for gaseous fuel, air, liquid fuel, and exhaust flow within the interface. Additionally, indicators followed along their respective paths on the LDI-DRS schematic. The block diagram also had a left-to-right trend, flowing from top-to-bottom with labeling and intuitive notations for ease of use. Consistent notation, labeling, and notes were all incorporated within the block diagram itself to explain various elements in the case of an uninformed researcher having to learn and use the operator code specific to this testing campaign.

There were eight core elements that the redesigned LabVIEW operator code needed to have incorporated to be considered operational. One, the code required start and stop controls with no timeout function. This enables the code to only run if the start control is selected first, and the code does not stop after a specified time. Rather, the code uses temperature and pressure thresholds as safety checkdowns, forcing the system to shut down if exceeded. The user can also stop the code manually. Two, the code must interpret air inlet and exhaust temperatures. One such safety checkdown is associated with the exhaust temperature. In the case of exhaust temperatures reaching greater than 90°C, the system's liquid fuel solenoid valves close, preventing further combustion, and protecting the building's exhaust fans. Three, toggleable controls must be implemented for the gaseous and liquid fuel solenoids such that fuel input can be controlled from the interface. Four, the code must incorporate an air mass flowrate setpoint for the system's mass flow controller. Five, accompanying the controls, mass flowrate indicators must be present to show the real-time mass flowrate fluctuations for both air and liquid fuel as these values directly influence the equivalence ratio. Six, pressure indicators showing the real-time pressure of the liquid fuel lines must be incorporated. Seven, the main fuel equivalence ratio needs to be visually and numerically displayed as the ER is the crucial value to be recorded throughout hot fire testing. Lastly, element eight, a write-out operation is required such that all desirable data is recorded for analysis. The redesigned operator code interface is displayed in Figure A.2 demonstrating that the code meets the required elements.

All eight operations were tested in cold flow conditions during the Fall 2023 semester and deemed fully operational, insinuating that the operator code developed was operational. However, hot fire testing in late Spring 2024 demonstrated that the code needed to be revised. New elements, beyond the original eight, have been stipulated post functionality testing. These elements will be discussed in the Future Efforts section of the report.

Motivation for Change in Project Scope.
Before experimentation commenced, a hot fire test of the LDI-DRS combustion chamber testing apparatus was attempted to ensure the functionality of the revised LabVIEW operator code and the rig itself. While the test proved the code to be functional, kerosene failed to flow out of the BETE PJ6 injector, preventing flame propagation within the glass flame tube of the rig. Additionally, the pressure transducers along the kerosene fuel line showed irregular pressure readings. The pressure transducer upstream of the PJ6 injector and downstream of the kerosene fuel solenoid was reading values of approximately 200psi when they should have been reading 0psi as the fuel line was exposed to atmospheric pressure. After further investigations of the fuel line and the pressure transducers, the fuel nozzle was deemed to be clogged and one of the three primary pressure transducers broken and in need of replacement. While a spare pressure transducer was able to be installed, correcting the pressure reading issue, the clogged fuel lance was far from an easy fix.

Throughout the two years working in Dr. Meadow's LDI research group, at least five fuel lances have clogged, not including the original one that functioned for several testing campaigns prior to my arrival. Previous experiences have demonstrated that whenever one of the LDI-DRS system's fuel lances clog, testing must be brought to a halt, the rig must be disassembled, a new fuel lance must be manufactured, and the new fuel lance had to be reinstalled. This process was not only costly, but it was time intensive, two resources that the group lacks extensive amounts of. Therefore, as PI, Dr. Meadows requested that a new fuel lance be designed such that time and money spent on replacement fuel lances are minimized.

Milestone Two: LDI-DRS Redesign.
Fuel Lance. Prior to this research project, the issue of clogged fuel lances had proven to be an unpredictable occurrence that would not only halt testing campaigns but skew data due to irregular fuel flow. However, through extensive discussion with welder Matt Collins, machinist Randal Munk, and machinists and professional welder Todd Stewart, it was concluded that internal corrosion from the welding and brazing processes was the most likely cause of the clogged BETE PJ6 injectors. This belief was taken into consideration during the redesign of the fuel lance.

The redesigned fuel lance allows for the adapter and fuel tube to be welded and thoroughly cleaned prior to the installment of the PJ6 injector. The previous fuel lance design required that the PJ6 injector be welded to an adapter and then to the fuel tube, allowing for unwanted internal corrosion to accumulate between the injector's filters and orifice. With the redesigned fuel lance, if PJ6 injector were to clog, the injector can be unscrewed, and filters replaced, while the tube and adapter are recleaned. Adversely, the PJ6 injector could be replaced in its entirety if preferred. In either instance, no additional welding or manufacturing is required to disassemble and reassemble the fuel lance, unlike with previous fuel lance designs. Furthermore, the new design no longer requires the Swagelok fittings and fuel tube below the plenum be cut away for the repair of a clogged fuel lance. The injector can be unscrewed from the adapter and removed from the system, allowing the fuel lance to be cleaned and injector repaired or replaced. A model of how the new fuel lance (injector, adapter, ball bearing, and fuel tube) interacts with the LDI-DRS system's swirler is displayed in Figure 4.

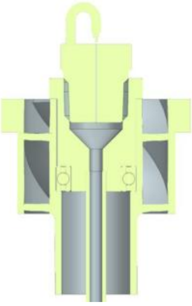

Figure 4. Redesigned fuel lance fitted inside swirler

Economic analysis yielded that the redesign would save the group money over time as replacement fuel lances are needed, Figure 5. The redesign is also less likely to require complete replacement.

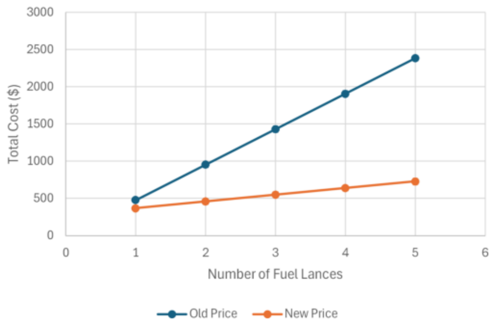

Figure 5. Total cost for old design and redesigned fuel lances.

Swirler. The swirler of the LDI-DRS system had to be adjusted to accommodate the redesigned fuel lance. Each of the diameter dimensions critical to the swirler redesign were labeled as denoted in Figure 6.

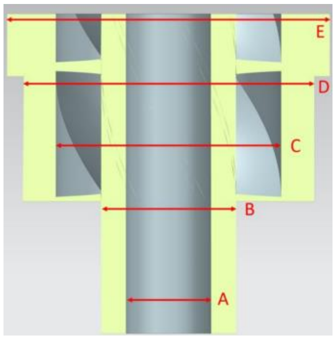

Figure 6. Critical swirler dimensions, shown in Table 1.

As per Dr. Meadows' request, the cross-sectional area of the swirler's flow path, the dimension associated with the difference of diameter C and diameter B, was kept constant across iterations. Maintaining constant cross-sectional area was accomplished using the equation for annular cross-sectional area described as

$$A_{cs} = \frac{\pi}{4} \cdot ({D_C}^2 - {D_B}^2) \qquad (1)$$

Additionally, diameter D and diameter E were kept constant across iterations such that the swirler would still fit within the existing ball bearing. To achieve the optimal design, the A-to-B and C-to-D wall thicknesses were reduced to a thickness no smaller than 1mm, then A was manipulated such that a standard-sized ball bearing would fit around the adapter and within the swirler. The final dimensions of the swirler that accompanies the redesigned fuel lance are in Table 1.

Table 1. Final swirler dimensions – first and final iteration

Diamaters	**Value (mm)**	**Value (in)**	**Value (mm)**	**Value (in)**
Swirler_A	12.875	0.5069	12.700	0.5000
Swirler_B	14.875	0.5856	14.700	0.5787
Swirler_C	22.825	0.8986	22.712	0.8942
Swirler_D	24.825	0.9774	25.000	0.9843
Swirler_E	30.000	1.1811	30.000	1.1811

After the core dimensions of the swirler were derived, the mechanical connection between the swirler and the DRS drive shaft that spins the swirler needed to be improved. With the previous configuration, the swirler purely relied on 0-80, 5/32" long set screws to prevent the swirler from slipping around the drive shaft or lifting vertically out of position during rotation. After extensive discussion with machinist Todd Stewart and testing, the swirler proved to be slipping, which would likely skew future data as actual rotational velocities would not align with their set points. The solution pursued for this project was to create a lock-and-key, manual connection between the swirler and the drive shaft as shown in Figure 7.

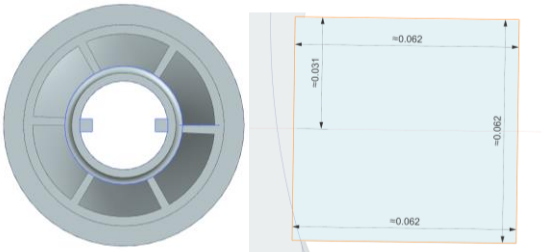

Figure 7. Swirler (bottom view) with two 0.062”x0.062”x0.402” keys

Milestone Three: Functionality Testing. After months of design work and manufacturing, the LDI-DRS testing apparatus was reassembled following the schematic in the system’s SOP. Both liquid and gaseous fuel lines were pressure tested using water and cleaned by flowing pure nitrogen through the liquid fuel lines. The fuel lance and liquid fuel tank were both cleaned prior to hot fire testing.

Additionally, computational models were created to visualize the relationships between fuel flow rate, the pressure at which the fuel tank is set, the number of turns required on needle-metering valve used to manually control flow rates (i.e., the valve’s Cv values), and the pressure drop across the system and specifically the valve.

$$Q = C_V\sqrt{\Delta P/_{SG}} \qquad (2)$$

The plot created that best visualizes this relationship is shown in Figure 8.

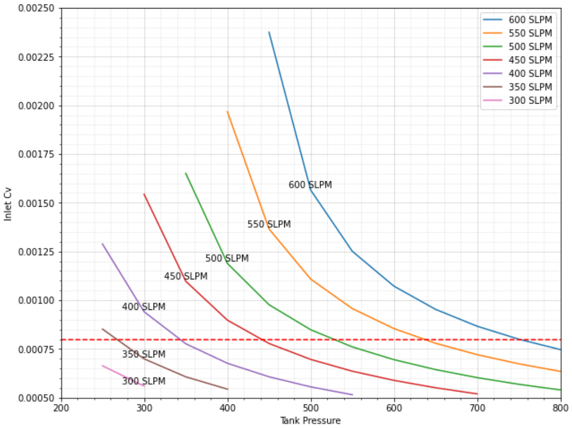

Figure 8. Needle metering valve inlet Cv as a function of tank pressure for various air flowrates.

For hot fire testing, the air flowrate, liquid fuel tank pressure, and needle-metering valve turns open were set following the trends displayed in Figure 8. Functionality testing proved that the re-designed fuel lance was capable of spraying liquid fuel. During testing, the LDI-DRS rig transitioned from the gaseous methane fuel to liquid kerosene, and the flame stabilized. Therefore, the re-designed rig demonstrated that it has the capability for LBO testing.

Future Efforts. The revised experimental scope will align with that of the initial project proposal. Future experiments will measure the effects that various converging-diverging venturi geometries have on the flow field and its recirculation zones. Swirl numbers will be varied using the group’s DRS modification. After the efforts of the Fall 2023 and Spring 2024 semesters, the LDI-DRS has been returned to a fully functional state and modified such that unclogging, and maintenance require a smaller time window to complete.

However, the new LabVIEW operator code requires further improvements that extend beyond the eight elements that were originally stipulated before the functionality testing can commence. Spring testing demonstrated that the code requires a calibration feature that subtracts out the noise in the flowrate and pressure measurements. Additionally, the code requires the dynamic pressure transducer be functional for acoustics measurements.

Once prepared, venturi testing will be conducted in hot fire conditions, and it will be compared to previous cold flow data collected by Dr. Aradhey shown in Figure 9.

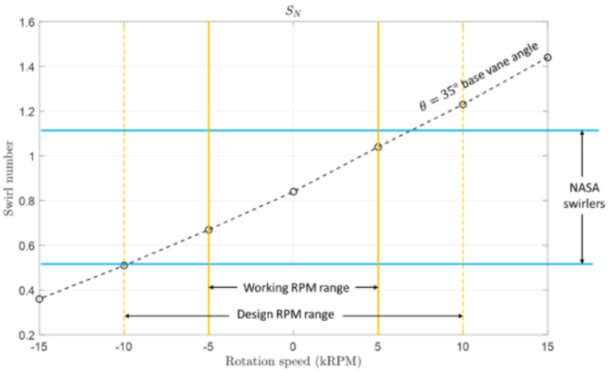

Figure 9. Cold flow data collected by Aradhey and team.

These tests will be followed by analysis of the various venturis and their effects on the flow field within a flame tube of the single-point first generation (SV-LDI-1) combustion chamber model. As presented, the primary apparatus needed for testing has been modified, and it has demonstrated that it can be used for further testing purposes.

Average gas-phase velocities will be measured using 2D planar PIV, and spray images will be captured during un-seeded hot-fire tests with the same PIV system. Flow field parameters of interest are swirl numbers and recirculation zones. These parameters will then be correlated to their corresponding spray characteristics via graphical analysis and visualization to investigate venturi effects on the spray characteristics. Spray characteristics of interest include: Spray shape, divergence angle, and droplet distribution. Flow field and spray characteristics will then be related to their corresponding LBO equivalence ratio to conclude the effects of venturi geometry on LBO limit. While the group has the PIV system required for testing, the test chamber will need to be outfitted to accommodate the system.

Acknowledgements. Similar to the starting point of many researchers, I began the Fall 2023 semester with training. I completed the *LabVIEW Core 1* modules to improve familiarity with LabVIEW design processes, read the PDPA manual to better understand the laser instrumentation used for flow field data collection, and familiarized myself with the testing apparatus, its electrical components, and the resources the group has available for system modifications and repair. However, something that I learned that is not often detailed is that as research goes on, so does training. As I progressed through the semesters, complications continuously arose, and they were often ones that my initial training did not fully help to overcome. I often found myself having to reach out to my PI, fellow researchers, machinists, and experienced engineers to solve the problems that came about during the semesters. My progress throughout the semesters was stimulated via the teachings of Dr. Meadows and the students within his research group during weekly meetings as well as through independent meetings with professors, machinists, and engineers with decades of collective experience in their respective fields.

Prior to the commencement of this undergraduate research study, I gained knowledge in LDI combustion technology from Dr. Meadows and Dr. Aradhey in various testing campaigns. It was through the shadowing of these mentors that I learned much of my practical, hands-on research experience. Furthermore, I gained additional testing experience during the Fall 2023 semester shadowing Dr. Meadows and Ashwin Kumar during other testing and system modification campaigns related to the group’s LDI combustion technology.

I gained technical experience with LabVIEW coding, a software that I had very limited experience with prior to the project, and CAD modeling in Siemens NX from Dr. Aradhey and Ashwin Kumar. I gained knowledge surrounding the relationship between manufacturing and mechanical design from experienced mechanical engineer George Stroud, machinist and professional welder Todd Stewart, machinists Randal Munk, and welder Matt Collins.

Late in the Spring 2024 semester, I witnessed the result of countless hours of design efforts with the manufactured fuel lance and swirler. I faced and overcame various challenges during assembly, fit check, and pressure testing. Dr. Meadows and I witness the rig start and stabilize a flame in the LDI-DRS flame tube, proving that the rig is once again ready for testing for the first time in nearly eight months. That ignition would not have been possible without the efforts of my team, and my sponsors, the people at the Virginia Space Grant Consortium.

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Appendix A:

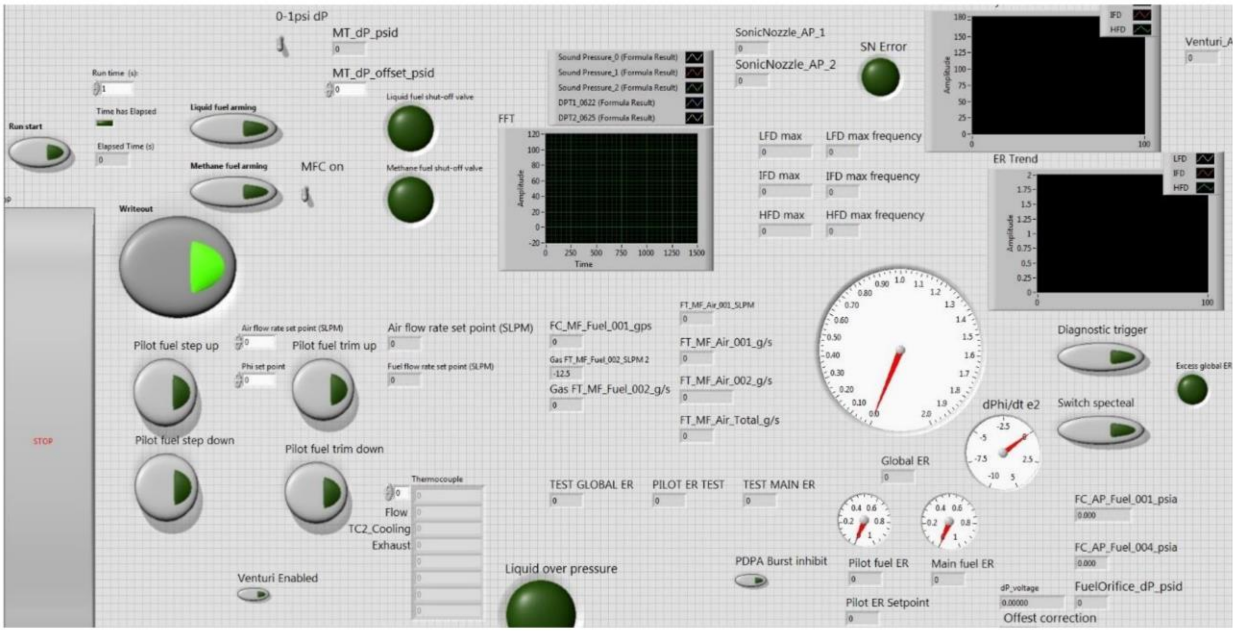
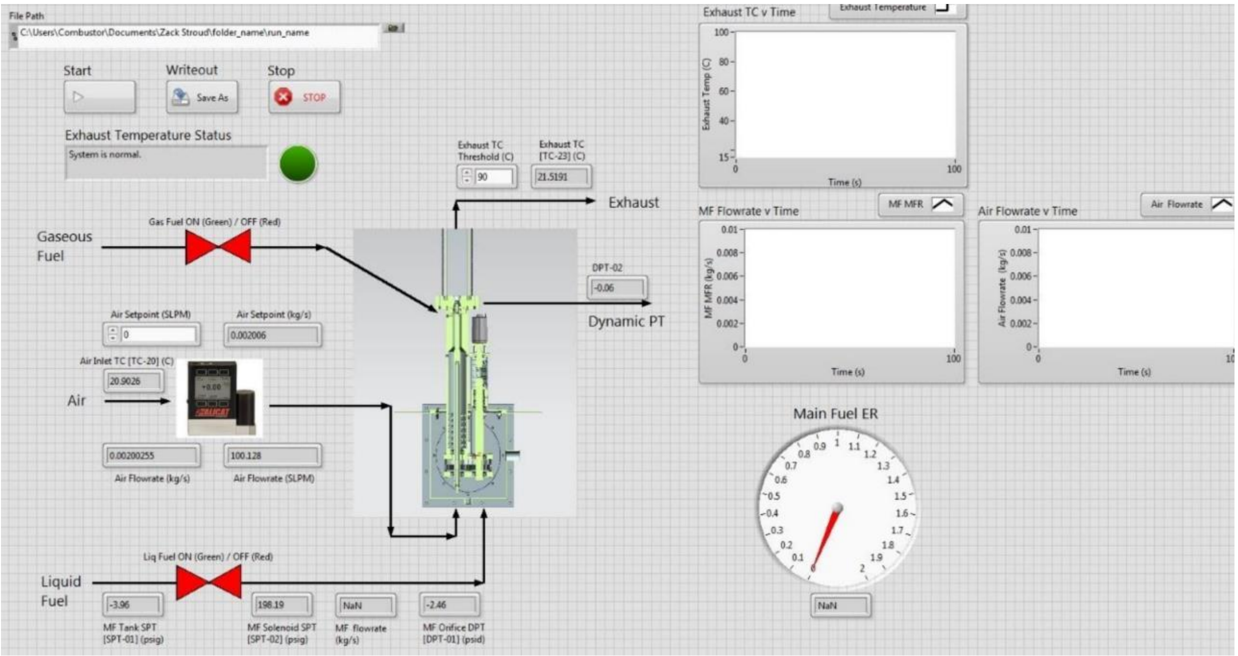


Figure A1. Previous LabVIEW operator code for the LDI-DRS combustion rig



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Exhaust Temperature Status: System is normal.

Exhaust TC Threshold (C): 90

Exhaust TC [TC-23] (C): 21.5191

DPT-02: -0.06

Air Setpoint (SLPM): 0

Air Setpoint (kg/s): 0.002006

Air Inlet TC [TC-20] (C): 20.9026

Air Flowrate (kg/s): 0.00200255

Air Flowrate (SLPM): 100.128

MF Tank SPT [SPT-01] (psig): -3.96

MF Solenoid SPT [SPT-02] (psig): 198.19

MF Flowrate (kg/s): NaN

MF Orifice DPT [DPT-01] (psid): -2.46

Main Fuel ER: NaN

Figure A2. Revised LabVIEW operator code for the LDI-DRS combustion rig