Development of an Experimental Combustor for Hybrid Electric Gas Turbines

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ABSTRACT

Future aircraft will require innovative propulsion architectures, such as hybrid electric gas turbines, for improvements in emissions and fuel economy. Hybridized propulsion systems impose novel operational constraints for the gas turbine, such as lower turndown ratios or sub-idle operation. Recent system-level studies have shown the feasibility of such architectures, but not the detailed combustor-level considerations. One particularly promising future aviation combustor concept is axially staged partially-premixed fuel injection, which is enabled by advances in additive manufacturing and sustainable aviation fuels. This paper describes facilities to develop a better understanding of axial fuel staging and the potential benefits it may provide. Two facilities have been developed to investigate different subsets of the relevant fundamental physics behind fuel staging. In particular, the success of fuel staging is highly dependent on both the nature of the fuel atomization in the coflowing staged air, but also the mixing of this staged air-fuel mixture into a vitiated crossflow. One facility was designed to study hybridized spray-in-coflow and spray-in-crossflow configurations and the second facility to assess the impacts of staged-fueling strategies on key combustor operability and turbine durability metrics, including flame shape, CO and NOx emissions, and turbine inlet temperature pattern. The facilities employ proven high-speed optical diagnostics and standard emission sampling methods to study the associated fluid mechanics and combustion dynamics. Additionally, innovative laser absorption-based measurement techniques can similarly be applied to resolve previously inaccessible spatial and temporal temperature profiles of the combustion products impinging on the turbine vane. This testbed can simulate a range of practical hybrid engine operating conditions. The contribution of this paper is to introduce new experimental testbeds for axially staging liquid fuels in aviation combustors and to detail the considerations that drive the facility and test design.

INTRODUCTION

Turbofan engines power much of the commercial aviation industry - a sector that is traditionally difficult to decarbonize. Electrification of aircraft has the potential to reduce the energy requirements, emissions, and noise associated with the growing aviation industry. Given expected technological advances in the next few decades, hybrid-electric propulsion (HEP) can help realize some of these benefits and the field has garnered significant research interest. Countless studies from various research groups have shown that HEP aircraft can reduce fuel burn over the course of a flight (Sarlioglu and Morris, 2015; Isikveren et al., 2015; Perullo et al., 2019; Atanasov and Silberhorn, 2020). Studies have shown that
a fully electric aircraft is not feasible for certain missions and that a more viable solution for decarbonization is a mildly parallel hybrid configuration, where there is an interaction between the conventional engine and the battery system, like many hybrid automobiles (Perullo et al., 2014; Gladin, Trawick, Perullo, Tai and Mavris, 2017; Gladin, Perullo, Tai and Mavris, 2017; Gladin et al., 2018; Perullo et al., 2019). Given the expected improvements in battery and motor technologies in 2030-2045, a 1-megawatt battery and 2-megawatt electric drive systems on each turbofan could be feasibly implemented on 50-200 passenger aircraft (Perullo et al., 2019). These electric motors could be partially powered by the gas turbine and could yield up to a 20% decrease in fuel burn relative to similar time-frame, non-hybridized, gas turbines, which could offset 20-30% of the aircraft’s cruising and climbing thrust requirements (Perullo et al., 2019). This hybridization and parallelization translate to a decreased maximum power output requirement from the gas turbine’s combustor. Turndown in an aircraft is a critical constraint and engineers must design combustors to stably operate in low-power configurations without sacrificing reliability, efficiency, or emissions at higher power operation. HEP engine cycles may admit new turndown requirements (Hathaway et al., 2013; Atanasov and Silberhorn, 2020). For example, the combustor may not need to produce as much thrust at take-off, when some of the thrust is supplied by the electric fans. Additionally, it may need to idle at a lower thrust level when performing an electric-taxi, or using the onboard battery for environmental and auxiliary systems (Sarlioglu and Morris, 2015; Atanasov and Silberhorn, 2020). Alternatively, higher thrust idles may be required when the Brayton cycle is being used to power the fans and charge the battery (Roberts and Therkelsen, 2014; Perullo et al., 2019). In short, HEP engines will likely face new turndown requirements.

The design space created by HEP turndown requirements has similarities to that of ground power turbines. Conventional lean, premixed, prevaporized (LPP) ground power turbines typically only operate between 80-100% load due to an increase in NOx emissions above emissions regulations at lower loads (Sirignano et al., 2019; Lieuwen, 2021b). Fuel staging allows these turbines to operate at lower loads, with lower flame temperatures, while maintaining low CO emissions (Sirignano et al., 2019). Adapting and combining technologies, such as LPP combustion and fuel staging to aviation engines may allow significant reductions in aircraft NOx emissions (Lieuwen, 2021b).

LPP designs are generally unavailable to modern aviation engines due to lean blowout margins, vaporization of liquid fuels at low compressor discharge temperatures, carbon monoxide emissions, combustion instability, flashback concerns, and variability in the thermo-fluidic properties of upcoming sustainable aviation fuels (Lefebvre and Ballal, 2010; Foust et al., 2012). Fuel staging is not currently employed in aviation engines due to technical challenges with fuel delivery and increased manufacturing complexity (McKinney et al., 2007). However, the implementation of these lean distributed combustion strategies could now be warranted by the new load ranges afforded by HEP cycles and enabled by advances in additive manufacturing and sustainable aviation fuels.

The advanced HEP combustor invites a clean-sheet redesign of aviation combustors to feature substantially premixed fuel and air staging and scheduling. For example, axial fuel staging, or axially controlled stoichiometry (ACS) is a promising technology for future combustors. For example, the fuel delivery system for ACS can keep the combustor primary zone lean throughout the whole range of operation, which may have benefits to NOx and particulates at higher powers. This is especially useful for HEP cycles with sub-idle operation, where the ACS can be sized to extend turndown. The effects of ACS have recently been explored in experimental aviation turbines by Japan Aerospace Exploration Agency (JAXA) (Yamamoto, Shimodaira, Yoshida and Kurosawa, 2013; Yamamoto, Shimodaira, Kurosawa and Yoshida, 2013) and P&W (Kramer, 2020; Smith, 2020). Their ACS schemes have been shown to significantly lower NOx emissions relative to traditional LPP and RQL-style combustors. Premixing, residence time, and flame temperature explanations have all been theorized for why these configurations yield less NOx. These effects have been extensively shown to be the key driving factors in reducing NOx (Cheng et al., 2000, 2009; Goh et al., 2019; Sirignano et al., 2019; Lieuwen, 2021b). However, there have been no experimental observations of fluid or combustion dynamics to support these hypotheses or determine the relative effect of each (He et al., 2020; Yamamoto, Shimodaira, Kurosawa and Yoshida, 2013). Additionally, there is only one known experimental study of the turbine radial temperature pattern, though with limited spatial resolution and no temporal resolution (Yamamoto, Shimodaira, Yoshida and Kurosawa, 2013). Furthermore, there are only a few limited computational studies of distributed combustion concepts at aircraft relevant operating conditions (Kramer, 2020; Smith, 2020).

This paper describes the development of two experimental facilities that are designed to simulate a single sector of a HEP gas turbine and study subsets of the relevant fundamental physics. These optically accessible test articles allow for direct observation of the fluid mechanics and combustion dynamics that arise from various fuel staging strategies. The facilities can also measure each scheme’s impact on CO, NOx, and soot emissions and the spatio-temporal temperature profile impinging on the turbine vanes. These quantifiable metrics can evaluate the performance of various clean-sheet combustor designs that are optimized specifically for hybrid aircraft engines.

**FACILITY DESIGN OVERVIEW**

The experiments are conducted in two different test rigs in the high-pressure test cells at the Ben T. Zinn Combustion Laboratory at Georgia Tech. The air system can deliver high-pressure air, up to 720 PSIG (50 barg), at temperatures up to 1000 °F (800 K) to each cell (Jovel et al., 2017). Jet-A fuel is also supplied to the test cells at pressures up to 450 PSIG (31
bar). This allows tests to be performed at, or close to, realistic engine conditions. The experiments are controlled from an adjacent cell via a LabVIEW cRIO data acquisition device to allow real-time sensing, processing, and control. Air flowrates are metered with Rosemount 8800D Vortex flowmeters and controlled with pneumatically actuated Emerson globe valves, which provide continuously variable flow resistances to the blowdown system. This allows for air control and metering, with 95% certainty, to within ±0.20% of the steady-state flowrate. Fuel is metered and controlled by Alicat CODA and Bronkhorst M15 Coriolis flow controllers with standard accuracies of ±0.6% and ±0.2%, respectively, of the steady-state flowrates. Pressures and temperatures are measured throughout the system with Omega PX309 pressure transducers and type-K thermocouples which have accuracies of ±0.25% and ±0.075%, respectively.

Two optically accessible experiments have been designed to study HEP combustor concepts with ACS. Both experiments are rated to at least 10 bar with preheat temperatures up to 650 K. These are shown in Figure 1. One is designed to be a non-reacting testbed to study fundamental spray dynamics, fluid mechanics, and mixing behavior of various fuel injection techniques, as shown in Figure 1a. The core air flow goes from bottom left to top right and it consists of several constant area 12cm x 7.5cm flow conditioning sections, shown in yellow, and a test section, in pink, which is described below. The test section has a plenum below it for feeding in staged fuel and air. The other facility is a reacting single-sector combustor test rig to study the combustor performance and emissions. The reacting experiment is an evolution of other previously published experiments that have been tested and validated in great detail by previous projects (Rock et al., 2019; Chandh et al., 2021), shown in Figure 1b. The redesigned components, shown in blue, are discussed below. Otherwise, these facilities have similar instrumentation, metering, and operating capabilities. The reacting facility has additional water-cooled emission sampling capabilities. The rationale to develop a non-reacting facility was to study the details of atomization and mixing of a single staged fuel-air jet in a crossflow, without the additional physics of combustion and combustor fluid mechanics. The reacting tests will add these complexities to study the emissions characteristics and operability ramifications of the staged fuel-air jets.

**Figure 1 Overview of Experimental Facilities**

**CONSTRAINTS AND OPERATING CONDITIONS**

Small-core hybrid-electric engine cycles pose unique challenges and constraints on the combustor, but also create opportunities for new operating and fueling strategies that are inaccessible to contemporary engines. Some models of a mission profile show reduced turndown requirements for the combustor - meaning that the hybrid idle thrust requirement is higher than in conventional engines. This design is often associated with using energy in the fuel to spin fans, charge batteries, and operate onboard environmental and auxiliary systems (Roberts and Therkelsen, 2014; Perullo et al., 2019). This would limit the low-load operation of the engine and constrain it to a set of operating conditions more like those in conventional LPP turbines. However, other models show that HEP architectures may require even lower idle thrust, also known as sub-idle operation, which requires the engine to stably operate even further away from its full-load design point while maintaining low emissions. This kind of architecture is often associated with electric-only taxis and using battery power for environmental and auxiliary systems (Sarlioglu and Morris, 2015; Atanasov and Silberhorn, 2020). Regardless of which system is shown to be more beneficial, HEP cycles will constrain engines to a unique set of operating conditions that are not required of modern engines. These novel conditions enable novel combustor architectures that can be tailored for optimal performance at multiple part-load and full-load design conditions.

**Staged Combustion**

Axially staged combustion is used in ground power turbines to accommodate low- or part-load operation while meeting stringent emissions requirements (Sirignano et al., 2019). Fuel staging in LPP ground power turbines has been shown to reduce NOx emissions by tailoring the stoichiometry and flame temperature distribution in a combustor across a range of
operating conditions (Goh et al., 2019; Sirignano et al., 2019). This operational flexibility is crucial for the adoption of HEP architectures, due to HEP turndown requirements, and the requirement for low NOx production across a range of conditions (McKinney et al., 2007; Hathaway et al., 2013; Atanasov and Silberhorn, 2020). There is also experimental evidence to suggest that fuel staging may allow for modulation and control over the spatio-temporal gas temperature distribution entering the turbine (Yamamoto, Shimodaira, Yoshida and Kurosawa, 2013; Yamamoto, Shimodaira, Kurosawa and Yoshida, 2013). This is critical for small-core gas turbines with more stringent cooling budgets (Bunker, 2006; Hathaway et al., 2013). Additionally, fuel staging has been tested and shown to admit lower overall fuel-air ratios, 0.007, and therefore lower thrust idle and sub-idle operation than conventional aircraft engines, where idle fuel-air ratios are approximately 0.020 (Yamamoto, Shimodaira, Yoshida and Kurosawa, 2013; Lieuwen, 2021a).

Many modern aviation engines employ a rich-burn, quick-quench, lean-burn (RQL) style combustor. This air-staged combustion approach relies upon quickly diluting a stable rich burning zone with air to create an overall lean engine to avoid producing thermal NOx. Even though the global equivalence ratio in the rich burning zone is high, the local equivalence ratio, due to the nature of non-premixed, or diffusion, flames, is stoichiometric. This results in local burning at high flame temperatures with significant thermal NOx production (Cheng et al., 2000, 2009; Lieuwen, 2021b). Shorter residence times have also been shown to be critical for reducing thermal NOx production (Cheng et al., 2000; Goh et al., 2019, 2021). ACS aims to premix fuel and air as thoroughly as possible to avoid diffusion flames, but even with no premixing, may still yield NOx reductions through residence time reductions (Goh et al., 2019, 2021).

Studies have shown that incorporating liquid fuel staging with existing air staging at aircraft engine conditions, could offer additional opportunities to reduce NOx relative to RQL levels (McKinney et al., 2007; He et al., 2016; Herbon et al., 2017; Kramer, 2020; Smith, 2020; He et al., 2020). ACS has also been shown to reduce NOx and smoke number in LPP combustors, especially at part-load conditions (Yamamoto, Shimodaira, Yoshida and Kurosawa, 2013; Yamamoto, Shimodaira, Kurosawa and Yoshida, 2013). Staged configurations have traditionally been disfavored due to their mechanical complexity and the difficulty of tailoring these systems across a wide operating envelope (McKinney et al., 2007). However, the reduced turndown associated with HEP cycles, recent advances in additive manufacturing to integrate fuel passages into the combustor, and the potential to reduce coking issues with sustainable alternative fuels (SAFs) mitigate these concerns of complexity. Routing fuel to portions of the combustor that were previously inaccessible consequently accommodates the prospect of using fuel as a coolant for these portions of the combustor (Boehm et al., 2021). Studies on near-term sustainable aviation fuels indicate the potential for reduced coking tendency, and possibly co-optimization for these distributed combustion schemes via improved thermal stability (Boehm et al., 2021). These advances in additive manufacturing and fuel characteristics are enabling technologies that eliminate many of the traditional barriers to ACS.

Hybrid Cycle Conditions

The facilities discussed in this paper were designed to operate at conditions corresponding to those from an estimated HEP engine cycle for a regional aircraft. Researchers at Georgia Tech’s Aerospace Systems Design Lab have over two decades of experience simulating engine cycles using their proprietary modeling tools (Perullo et al., 2019; Nunez et al., 2021). For sizing this experimental combustor, a single sector of their P&W 1133G turbofan system model was used to calculate compressor discharge temperatures, pressures, and flowrates, as well as fuel flowrates across a matrix of 13 throttle settings, between 0-100%, and 5 flight conditions: the aerodynamic design point, top-of-climb, take-off, and sea-level static, and sea-level without compressor bleeds. Their cycle deck accounts for an estimated reduction in core sizes and thrust due to both hybridization and predictions of technological advancements in the year 2040. The engine produces 82kN of thrust at takeoff with an overall pressure ratio of 44. The airflow rates and fuel-air ratios at 7%, 30%, 85%, and 100% of takeoff thrust are 6.98 kg/s, 12.6 kg/s, 23.2 kg/s, and 25.7 kg/s and 0.0146, 0.0207, 0.0295, 0.0314, respectively (Perullo et al., 2019; Nunez et al., 2021). Each of these 65 conditions was further adjusted from the P&W1133G cycle conditions for the experimental facility’s operating conditions by matching the flow parameter or combustor inlet Mach number, where all values correspond to stagnation conditions entering the combustor after compressor bleeds have been removed. The bulk velocity of the gas can be related to mass flowrate and pressure via the ideal gas law. Matching the inlet Mach number, for a fixed inlet swirlier geometry and gas, allows for a mass flowrate scaling given a pressure and temperature ratio, as shown in Equation 1, where subscripts “exp” and “cycle” refer to conditions achievable in the experimental facility and engine cycle model data, respectively. The inlet swirlier geometry can be assumed to be fixed because the experimental hardware, described below, was designed to match those found on contemporary P&W engines.

\[ \dot{m}_{\text{exp}} = \dot{m}_{\text{cycle}} \left( \frac{T_{\text{cycle}}}{T_{\text{exp}}} \right) \left( \frac{P_{\text{exp}}}{P_{\text{cycle}}} \right) \]  

This reduced some of the operating temperatures and pressures, so they could safely and reliably be tested in the combustion test cells, \(T_{\text{exp}} = 625 \text{ K}\) and \(P_{\text{exp}} = 7 \text{ bar}\). The resulting matrix of 65 testable flight conditions needed to be further downsampled by considering limiting conditions for fuel staging and LPP concepts.
Air Fuel Scheduling

Even though HEP architectures decrease the turndown required of the gas turbine combustor, the engine must still be able to sustain a stable flame under all conditions. Therefore, the leanest condition in this matrix, 0% throttle at sea level, guides much of the combustor design to avoid lean-blownout.

This experimental HEP combustor was designed around an existing additively manufactured high-shear dual-radial swirler. The fuel injector consisted of a primary pressure atomizing tip with 6 circumferentially distributed secondary airblast atomization streams, which impinge and prefilm upon the inner wall of the swirler (Cohen and Rosfjord, 1993). This project uses a public swirler that was developed under the FAA ASCENT 55 program (Lieuwen, 2021a).

Anticipated operation at low power conditions required the secondary spray to be turned off so fuel is only delivered through the pressure atomizing tip to maintain appropriate atomization and flame stability. Therefore, in this HEP combustor, the limiting leanest case required that all the scheduled fuel is delivered through this primary orifice and the combustor geometry must enforce an air split so that this pilot flame doesn’t blow off. Previous studies have operated similar fuel injectors and swirlers at equivalence ratios of approximately 0.7 without experiencing instabilities (Chandh et al., 2021; Lieuwen, 2021a). This number could therefore be used as the lean-limiting condition. However, for fuel staging to have the greatest potential NOx reduction across the entire flight envelope, the cycle must permit significant amounts of staging at cruise conditions - where most of the NOx is currently emitted and where NOx has the most significant greenhouse effect (Foust et al., 2012). This, combined with the low compressor discharge temperatures at this stationary low power condition, resulted in an initial estimate that the low-power head-end equivalence ratio must be 0.9. This constraint relaxes to 0.7 at higher power conditions with higher compressor discharge temperatures. During low power operation, this near-stoichiometric burning may produce more NOx for the short period that the aircraft is at these conditions but may yield an overall decrease in NOx over a typical mission. Future work will use data from these testbeds to optimize this equivalence ratio to create the greatest decrease in NOx across a typical flight profile.

The adjusted cycle model dictated that the total combustor fuel and airflow at this condition are 0.371 g/s and 299 g/s, respectively. To achieve this equivalence ratio, using a stoichiometric multiplier of 14.69 for Jet-A, the maximum allowable swirler airflow is 0.61 g/s or about 20% of the overall core air (Saggese et al., 2020). The remaining 80% of the air budget therefore must be diverted to effusion cooling, dilution, or pre-mixing with any staged fuel, and for the rest of this paper will be referred to as “staged air”. One further constraint imposed by this hardware is the fixed swirler geometry and therefore fixed effective flow area, or $AC_d$. Assuming the swirler air and the staged air experience similar pressure drops entering the combustor, the overall $AC_d$ of the staged air passages in the combustion liner is calculated using the standard formula for the incompressible discharge coefficient, shown in Equation 2. Here, the density is calculated at the adjusted inlet conditions. This calculation fixed the geometric aerodynamic parameters of the combustor, which consequently, guided air splits at all conditions, not just this lean limiting case.

$$(AC_d)_{liner} = \frac{m_{air, staged}}{\sqrt{2\rho \Delta P}}$$

The head end equivalence ratio requirements set the HEP cycle’s fuel staging so that up to 69% of the total fuel could be staged at the highest power conditions and between 61% to 66% could be staged at cruising conditions. This, combined with the fixed airflow split, resulted in equivalence ratios of the staged fuel-air mixture between 0.28 and 0.34 for typical cruise operation. This testbed can study various strategies for staging this balance of fuel and air to see whether each scheme produces less NOx than nonstaged combustion schemes at similar power levels. To study the NOx produced at each condition, a special emission sampling component was designed and discussed in a later section.

NONREACTING TEST FACILITY

The non-reacting test facility, as discussed previously, is intended to study the effects of various fuel atomizers and air ducts on the atomization and mixedness of the staged air and fuel, without combustion effects. By selecting certain combinations of atomizers and ducts, a series of tests have been developed to study both aerodynamics and droplet breakup dynamics of the staged air-fuel injection.

Pressure swirl atomizers have been well studied in quiescent ambient environments but there have been few studies of the primary and secondary atomization processes in ducted coflowing environments (Lefebvre and McDonell, 2017). Studies have shown that droplet size and spray angle increase with high-momentum non-ducted co-flowing air at gas-turbine conditions, due to a recirculation zone near the injector surface that disrupts secondary atomization processes (Schäfer et al., 2021; Petry et al., 2022). There are also few known studies on the penetration of pressure-swirl atomizers in crossflowing environments, but they have been shown to behave differently than plain jets (Lefebvre and McDonell, 2017). There are also no known studies of ducted sprays in coflow that issue into a crossflowing environment. The staged combustion concepts tested in these newly developed facilities are evaluated to see how ducted coflow and crossflow momentums impact primary and secondary atomization processes, jet penetration, drop size, dispersion, and mixing, of various fuel injectors. The non-reacting facility is designed to rapidly study a wide range of parameters relevant to the subset of physics responsible for
these effects with a single pressure swirl atomizer in a ducted coflow and crossflow at conditions representative of staged combustors in aviation turbines.

Figure 2 Comparison of Atomizers and Ducts

Ducts

The staged fuel-air mixture may be affected by duct aerodynamics. In a HEP combustor, this staged air duct is the hole in the combustion liner through which staged air and fuel enter the combustor core. In a traditional RQL combustor, this duct would be referred to as a quench or dilution hole. This facility can accommodate various duct geometries to determine whether the air coflow characteristics impact the atomization and mixing of the staged fuel.

Ducted Fuel Injection (DFI) is a method of fuel injection, in reciprocating diesel engines, that has been shown to reduce soot formation (Mueller et al., 2017). Recent DFI studies have found that the duct geometry can impact the amount of soot formation (Gehmlich et al., 2018). There are several similarities between staged fuel injection in a gas turbine and ducted fuel injection in a diesel engine, however, there are several key differences. Notably, the differences between the mass flowrates and velocities of the fuel sprays and the presence of co-flowing staged air in a gas turbine as opposed to jet-pumping entrainment in diesel engines. However, this provides credence that there is potential for different duct geometries to impact staged fuel-air mixing.

The non-reacting facility can accept arbitrarily shaped ducts and so preliminary studies will focus on three fundamental geometries: a straight duct, a tapered duct where the inlet and outlet flow areas remain constant when accounting for the blockage area of an atomizer, and a venturi-shaped contoured nozzle with an inlet and outlet diameter that match those of the tapered duct. These ducts are shown in Figure 2b. These ducts also permit the atomizers to be immersed into the combustion liner wall at different depths. These ducts will create different aerodynamic environments for the spray and may impact the nature of the breakup. Evaluating gas properties at the duct inlet, via ideal gas law and Bernoulli’s equation, and using the duct outlet diameter as a characteristic length scale yields testable Reynolds numbers between 55,000 and 1,200,000 in this non-reacting facility.

Atomizers

Three hollow-cone pressure-swirl atomizers were chosen for this study - two from Spray Systems Co. (1/4LN-SS0.6 and 1/4LN-SS1) and one from Lee Company (NZSA1801120H). The 0.6 Spray Systems Nozzle, ”SS0.6”, has a calculated effective liquid resistance of 12643 ± 72 Lohms, while the 1.0 Spray Systems Nozzle, ”SS1”, has a flow resistance of 7591 ± 92 Lohms. The Lee Co. Spin Jet, ”Lee12”, had a nominal resistance of 12000 ± 1200 lohms. The manufacturers stated the expected cone angles as a function of the pressure drop across these nozzles when spraying into a quiescent ambient domain. Additionally, they also specify an expected range of droplet sizes, <150 microns and 10-500 microns, for the SS and Lee nozzles, respectively, when spraying room temperature water into a quiescent ambient flow. The nozzles can be compared in Figure 2a where the blue, orange, and pink lines represent the SS0.6, SS1, and Lee12 nozzles, respectively, across their respective working pressure ranges. The top plot compares the resulting flowrate through each nozzle due to its flow resistance, while the bottom plot compares the manufacturer-specified cone angles. The top plot shows that the Lee12 and the SS0.6 nozzle will both produce similar flowrates at the same differential pressure, but will likely have very different spray characteristics due to the different spray angles and manufacturers. The two SS nozzles will have more similar spray characteristics at the same flowrate but will have to operate at different pressure drops.
These nozzles were also chosen because 4 of them could be employed in a HEP cycle to achieve the required range of cruising and takeoff staged fuel flowrates while maintaining an acceptable pressure. The black dashed line in Figure 2a represents the required flowrate for each nozzle at a takeoff condition while the two black dotted lines represent the upper and lower flowrates for a typical cruise condition. It can be seen that the two SS nozzles can cover this range of flowrates, but have variable sensitivities to pressure drop. The Lee nozzle can almost cover the entire range of flowrates but may need to be paired with one of the SS nozzles to achieve a takeoff flowrate.

The different atomizers, despite having different geometries, reside in housings with identical external dimensions. Alternative housings can be manufactured for the smaller Lee nozzle to shrink the blockage area at the duct inlet for three additional ducts with smaller inlets.

\[ We = \frac{\text{Aerodynamic Drag}}{\text{Droplet Cohesion}} = \frac{8 \rho v^2 C_d \pi l^2}{\pi \sigma} = \frac{\rho v^2 l}{\sigma} \]  

The Weber number of a spray represents the ratio of aerodynamic drag forces to droplet cohesive forces that govern droplet breakup mechanisms. The definition and derivation of the Weber number for spherical droplets are shown in Equation 3. The range of operating conditions in the non-reacting facility yields a range of testable Weber numbers between 250 and 1,800. Here, the gas properties are evaluated at the duct inlet using ideal gas law and Bernoulli’s equation, the fuel’s surface tension at 315 K (Edwards, 2017), and the characteristic fluid length scale as the effective diameter of the atomizer orifice. If instead, the characteristic fluid length scale is taken to be the manufacturer quoted range of droplet diameters, the testable Weber number ranges for the SS and Lee nozzles are 16 to 1,800 and 16 to 550, respectively.

These nozzles and ducts allow for a test matrix that can isolate and study the effect of a single parameter, such as nozzle manufacturer, atomizer pressure drop, Weber number, and Reynolds number, on the staged mixture statistics, while holding other parameters constant. These three duct geometries, 3 atomizers, and 3 immersion depths will allow preliminary investigations of the aerodynamic and droplet breakup mechanisms responsible for atomizing and mixing the staged air-fuel mixture.

**Mixing Diagnostics**

This facility can easily employ various diagnostic techniques, both conventional and experimental, to study the mixing and flow characteristics of air-fuel jets issuing from where the yellow rectangle can be seen in Figure 3a. One such conventional measurement is particle image velocimetry (PIV), which can be employed in both side and top-down configurations. These 12.5cm x 7cm views are shown by the pink square and blue dashed lines, respectively, in Figure 3a. 1-micron Al₂O₃ particles can be used as tracer particles for the core or staged air. Fuel droplets can also be illuminated and the scattered light can be imaged for concentration measurements. The resulting images of Mie scattered light can provide planar slices or line-of-sight integrated measurements depending on the nature of the illumination source - either a planar laser sheet or diffuse backlighting.

More advanced techniques could be used to obtain quantitative liquid volume fraction measurements and droplet diameter distribution estimates via absorption, scattering, or fluorescence measurements of liquid droplets or vaporized fuel (Tropea, 2011; Linne, 2013; Fansler and Parrish, 2014; Poursadegh et al., 2020). These diagnostics can further help elucidate the mixing and flowfield physics that result in some staging schemes performing better than others and can help guide the reacting facility’s test matrix design.

To compare the mixing performance of each combination, a measure of concentration can be calculated and compared at 1 duct diameter from the duct exit. Additionally, the concentrations can also be evaluated and compared at a distance from the duct exit that corresponds to a bulk flow velocity multiplied by an auto-ignition time delay of the most reactive mixture fraction, assuming adiabatic mixing of the staged air and fuel.
REACTING TEST FACILITY

The reacting test facility, introduced previously, is intended to take the findings and insights from the non-reacting facility and determine how those mixing trends impact and are impacted by combustion. Though spray flames in either coflow or crossflow and premixed gaseous jets in crossflow have been the subject of intense research, there is limited information on partially-premixed reacting sprays in crossflow at gas turbine relevant conditions (Lefebvre and Ballal, 2010). The facility was similarly designed to accommodate many staging schemes, however, it is less focused on exploring the fluid mechanics of the staging schemes but rather on their effect on system-level optimization parameters, such as emissions and temperature pattern.

A modular test article was designed with replaceable panels on each of the 4 sides and is shown in tan in Figure 3b. This article corresponds to the upgraded components in Figure 1b and is similar to a previous test article developed under a public FAA project (Lieuwen, 2021a). These panels could accommodate glass windows for optical and laser access, solid walls, staged fuel atomizers, air ducts, probes, etc. In the displayed configuration, the flow, which goes from left to right, can be viewed through the side panels, one of which is visible in pink. Here potential staged injection locations are shown as yellow boxes while the conventional fuel circuits and air swirler are behind the orange box. Each of the other ducts from Figure 2b can also fit, with the help of an adapter, into the non-reacting experiment. This allows the same duct geometries and atomizers to be studied in both the reacting and non-reacting facilities.

Combustion and Fluid Dynamic Diagnostics

The optically accessible test articles allow for top-down and side views of the combustion process. Side views of the experiment can be seen in Figure 3b. The solid pink square represents a streamwise slice of the flow through the plane of symmetry with a field of view of 12cm x 8.25cm. Incidentally, this pink box also corresponds to the orientation of laser sheets that could be used to fluoresce or illuminate a planar slice of the flow. Additionally, lasers and cameras can be oriented in opposite configurations to look down on the flow. In these configurations, those laser sheets and image planes would look like the blue dashed lines in Figure 3b, with a depth into the page of 6.35cm.

Additional diagnostics, beyond those from the non-reacting facility, can be employed in the reacting rig to study heat release and temperature fields. Laser-induced fluorescence and chemiluminescence have been validated in similar combustors to study mixing and combustion physics (Cherev et al., 2017; Rock et al., 2020; Chandh et al., 2021). As discussed below, absorption measurements can explore the resulting temperature patterns of the flowfield and turbine vanes.

Exhaust with Integrated Emissions Sampling

A special post-combustor exhaust section was designed to simulate turbine inlet vanes, with internal water-cooling. This converging nozzle provides a realistic boundary condition for the combustor exit and chokes the flow leaving the test article. Additionally, these vanes support water-cooled sensing or sampling ports. This component and its internal features are shown in Figure 4. The flow area is the region internal to the light blue rectangle in Figure 4a and includes a bell-mouth converging section, 3 symmetric airfoil-shaped turbine vanes, and 12 pink tubes for spatially sampling the flow. The surfaces external to this rectangle are for mating to other components. Figure 4b shows a cross-section where the light blue represents the combustion product flow passages before and after the choke point, the dark blue internal geometry represents the water-cooled wetted surfaces, and the pink shows the sample tubes that travel through the water channels. This allows the pink sample probes to remain relatively cool and helps freeze the composition of their contents. A Horiba 350G gas analyzer samples CO2, CO, NOx, NO, and O2 concentrations according to SAE ARP 1256D and ARP 1553C standards (SAE, 2011, 2016). This design allows for real-time measurements of pollutant emissions, one of the performance metrics of each staging scheme. However, to understand the mechanisms that are responsible for each scheme’s performance, a test article was designed with optical access to study mixing and combustion dynamics.
**Temperature Pattern Measurements**

Another metric for evaluating the performance of each staging scheme is the pattern factor or at least measuring a qualitative spatial temperature distribution entering the turbine. This combustor-turbine interaction guides much of the combustor design and has significant ramifications for the durability and cooling required in the high-pressure turbine. However, due to the difficulty in experimentally determining the pattern factor, designers must only rely on computational models (McKinney et al., 2007). Most materials cannot withstand these environments, without some kind of external cooling. Therefore physical sensors are generally not a practical solution for obtaining this measurement. Instead, optical techniques must be employed. This combustor was designed with a modular pattern factor diagnostic ring, shown as the green component in Figure 3b. Multiple of these rings could be designed for housing different diagnostics. This modularity allows the experiment to compare how effective each diagnostic is at resolving the pattern factor. Additionally, this ring can be swapped for one that houses thermocouples. This would enable sparse validation cases with consumable exotic XTA-type thermocouples, to withstand extremely high gas temperatures.

The most promising non-intrusive method is two-wavelength absorption spectroscopy methods to measure the temperature of a selected gas species as it leaves the combustor. Tunable Diode Laser Absorption Spectroscopy (TDLAS) has been extensively studied and validated for temperature measurements of lab-scale flames (Goldenstein et al., 2017). Tomographic reconstruction from these gridded line-of-sight measurements can be achieved by solving an inverse problem, given some prior knowledge of the IR absorption characteristics of the water vapor in gaseous combustion products (Grauer and Steinberg, 2020). Many of the authors of this paper are testing a similar application of this diagnostic for a different aviation project (Lieuwen, 2021a). A partially transparent cross-section of the TDLAS diagnostic ring can be seen in Figure 4c, with opposing pairs of pitch and catch fiber optics in the green and orange holes. The fiber optic collimators are water-cooled by a serpentine passage highlighted in blue. Once validated, the same tools can be employed on this HEP combustor to obtain and compare the pattern factor of various staging schemes.

It remains to be seen whether, and to what degree, fuel scheduling schemes can affect the pattern factor. This may allow HEP engine designers to prescribe or anticipate different pattern factors at various operating conditions and allow for real-time changes to the cooling budget in the turbine. Given that the cooling budget already represents a larger portion of a HEP engine’s smaller core flowrate, and therefore a larger source of inefficiency, any data that can help reduce or anticipate the required cooling flowrates will help improve the HEP cycle performance (McKinney et al., 2007; Foust et al., 2012).

**CONCLUSIONS**

This paper presents the combustor-specific challenges and opportunities created by a hybrid-electric gas turbine cycle, with additive manufacturing and SAFs as enabling technologies. A cycle deck of a conventional gas turbine engine is adapted to the anticipated conditions in a HEP cycle and shows the potential for exploring distributed combustion concepts where up to 73% of the fuel is staged in the combustor. This staging is expected to yield lower NOx emissions than current RQL-style engines. Various nozzles and ducts for staging air and fuel can be studied in the non-reacting test facility to measure staged fuel spray atomization and mixing. A reacting test facility is developed to measure NOx production across these staging schemes and observe the fluid and combustion phenomena that may cause variations in emissions. Various other diagnostics can be employed to measure fuel concentration, flow velocity, heat release, and temperature fields. These measurements and test capabilities can evaluate and optimize the performance, in terms of emissions and pattern factor, of a HEP combustor with distributed fueling relative to contemporary non-HEP-optimized combustors.

**NOMENCLATURE**

- ACS - Axially Controlled Stoichiometry
- DFI - Ducted Fuel Injection
- GE - General Electric
- FAA - Federal Aviation Administration
- HEP - Hybrid Electric Propulsion
- LPP - Lean, Premixed, and Prevaporized
- PIV - Particle Image Velocimetry
- PLIF - Planar Laser-Induced Fluorescence
- P&W - Pratt & Whitney
- LII - Laser-Induced Incandescence
- RQL - Rich-burn, Quick-quench, Lean-burn
- RTTC - Ratheon Technologies Research Center
- SWIR - Short-Wave Infrared Radiation
- TDLAS - Tunable Diode Laser Absorption Spectroscopy
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