Project 065(B) Fuel Testing Approaches for Rapid Jet Fuel Prescreening

University of Illinois Urbana-Champaign

Project Lead Investigator

Tonghun Lee
Professor
Mechanical Science & Engineering
University of Illinois at Urbana-Champaign
1206 W. Green St.
Urbana, IL 61801
517-290-8005
tonghun@illinois.edu

University Participants

University of Illinois at Urbana-Champaign

- PI: Tonghun Lee, Professor
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- Tasks:
    1. Baseline ignition behavior of the M1 combustor (high-altitude testing)
    2. Fuel injection optimization

Project Funding Level

FAA funding level: $150,000
Cost share: 100% match provided by software license support from Converge, Inc.

Investigation Team

- Tonghun Lee, Professor, University of Illinois at Urbana-Champaign (UIUC): Overall research supervision
- Eric Wood (Graduate Student, UIUC), Caleb Trotter (Undergraduate Student, UIUC): Experimental efforts characterizing the M1 combustor, including laser and optical diagnostics

Project Overview

This study (Prescreening 65b) aims to introduce a new compact test rig (M1 combustor), developed with OEM support within the National Jet Fuel Combustion Program (NJFCP), that can screen fundamental combustor behavior for a much lower fuel volume (~gallons) prior to Tier 3 and 4 tests in the ASTM D4054 evaluation. In the NJFCP, the referee rig at the Air Force Research Laboratory (AFRL) was utilized as a foundational test rig for this goal. The M1 may have the potential to carry out these tasks at reduced fuel volumes (~gallons versus ~hundreds of gallons) in a simplified and open architecture that can be readily shared and operated at different locations at a fraction of the cost. Both the Army Research Laboratory (ARL) and Argonne National Laboratory (ANL) will be partners in the effort to fully characterize the M1 facility. If successful, these efforts will allow fuel providers and OEMs to conduct basic combustor tests using an identical testing architecture and identical test conditions at multiple test locations, in contrast to the referee rig, which is housed in a secure government facility (AFRL). Tests in smaller test rigs can provide a platform for each supplier or researcher to independently test their new fuels and to make predictions without requiring the use of one single facility. Over time, as test data are accumulated, the potential for test rigs, such as the M1 to predict actual Tier 3 and 4 performance, will increase and may reduce the burden of relying on capital-intensive ASTM rig and engine tests.

Background of the M1 Combustor

Under the FAA-funded NJFCP, the referee rig combustor at AFRL was used to determine the sensitivity of combustor performance parameters, such as lean blowout (LBO) and ignition parameters, to the chemical composition of novel fuels. The results from this investigation were instrumental in establishing a relationship between fuel chemistry and its impact on combustor performance. Professor Tonghun Lee's research group conducted a significant portion of the laser and optical diagnostic work for the referee rig as part of the NJFCP, including quantitative phase Doppler particle analysis, which provided key quantitative data for the simulation efforts.

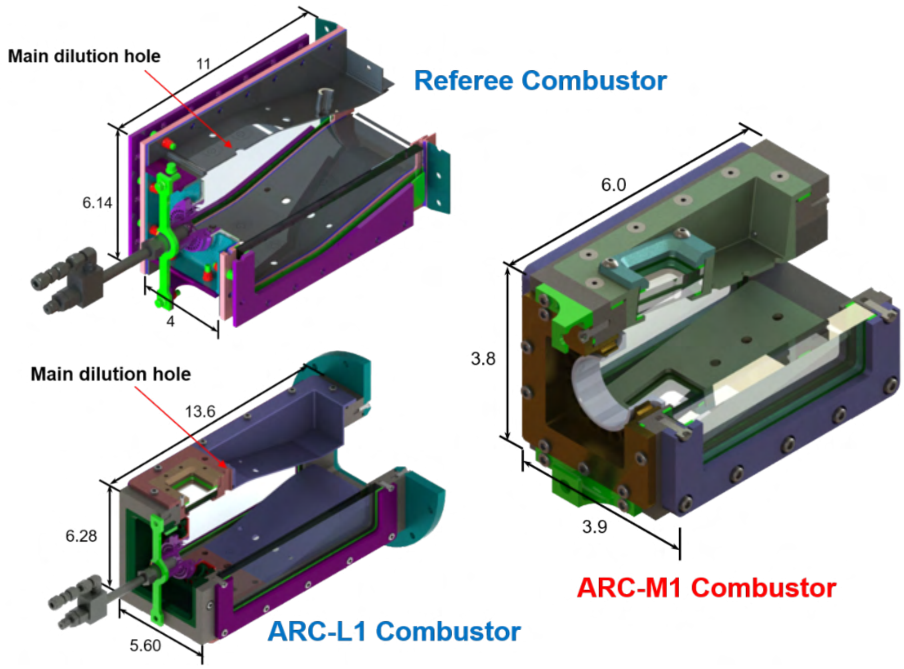

Figure 1. The referee combustor at AFRL, the ARC-L1 combustor, and the ARC-M1 combustor.

Simultaneously, the ARL team worked with NJFCP researchers to complement the referee combustor efforts by performing high-altitude relight tests at the ARL Aberdeen Proving Grounds, where a new altitude test chamber had just been commissioned. During the planning phase, ARL decided to build two new combustors to address some shortcomings of the referee combustor, namely, shortcomings related to optical access and flow split uncertainty. The first combustor would have the exact same dimensions as the referee combustor but with enhanced optical access and a less-complicated liner for air cooling. A lack of vertical optical access had made velocity field measurements in the referee combustor virtually impossible, and the complicated liner had caused difficulties in accurately predicting air flux into the combustor. This new combustor would be termed ARC-L1 (Army Research Combustor-L1). Additionally, an effort was made to build a smaller combustor for more flexible testing with less fuel and air requirements. This smaller version would be termed the ARC-M1, and the main architecture proposed in this study is based on this design. Both combustors were designed by a subcommittee composed of NJFCP researchers and OEM representatives. The construction of both combustors was originally conducted by the research group of the PI (Tonghun Lee) at UIUC.

The referee combustor, L1, and M1 are shown in Figure 1. Continuing this heritage, ARL will be a key partner in the analysis of this combustor in terms of both numerical simulation efforts as well as X-ray imaging of spray break-up, which will be performed at the Advanced Photon Source of ANL. In addition to the laser and optical measurements available at UIUC, the goal is to characterize the operating characteristics of the M1 combustor in an unprecedented way so that it can be widely adopted in the academic/industrial community as a test platform for new fuel blends. Once this characterization is complete, the basic physics, dimensions, and operational envelope of the combustor will be openly shared with the academic and commercial sectors. This work is expected to provide a common platform not only for prescreening sustainable aviation fuels (SAFs) but also for performing other sustainability-related experiments involving novel fuels in a laboratory setting.

Task 1 – Baseline Ignition Behavior of the M1 Combustor

University of Illinois at Urbana-Champaign

Objectives

The objective of this task is to establish baseline combustor ignition performance for the ARC-M1 combustor when operating under cold-start and altitude relight scenarios. Combustor ignition performance under suboptimal inlet conditions is a key performance metric that must be met to integrate SAF into any gas turbine system. These experiments represent an important first step toward establishing baseline ignition performance in the M1 combustor under these conditions using conventional jet fuel.

Research Approach

Overview of Experimental Altitude Relight Testing

To collect baseline ignition performance metrics on the ARC-M1 combustor, the ARL's altitude chamber at Aberdeen Proving Ground, MD was utilized to perform ignition testing under both ground cold-start and altitude relight conditions. The Small Engine Altitude Research Facility (SmEARF) can simulate altitudes of up to 30,000 ft, corresponding to chamber pressures between 0.30 and 1.00 atm and chamber temperatures from 229 K to 327 K. The air supply system can deliver up to 1.361 kg/s of dry air into the chamber for testing a wide array of engine types, including small piston and gas turbine engines.

The ARC-M1 combustor is operated inside the altitude chamber for this testing, with the chamber air inlet being connected to the combustor inlet by a large duct. A portion of the incoming chamber air is diverted to a bypass air stream, which does not pass through the combustor and is instead used to help maintain the desired ambient temperature inside the chamber. The combustor dilution jets are supplied from manifolds that divert a supply stream from the main combustion air. While this experimental setup does not allow direct mass flow control of the air flowrate through the combustor during testing, the pressure drop across the combustor correlates with measurements made through the system ahead of time using a laminar flow element condition where testing is conducted. Figure 2 shows a picture of the SmEARF altitude chamber and the combustor installed within the test chamber. During testing, the fuel is chilled to testing temperatures by using an air-driven pump that drives the fuel through a cooling loop, where a Thermonics -60°C two-stage chiller and brazed plate heat exchanger cool the fuel to the desired temperature. The fuel flowrate through the cooling loop is controlled by a Bronkhorst M15 0-300 g/min flow controller. Fuel from the chilling loop can be directed into the combustor by actuation of a three-way solenoid valve. The fuel pressure in the cooling loop is maintained by a proportional solenoid valve to ensure that the system is at the correct pressure when fuel injection begins.

To understand combustor ignition behavior in the ARC-M1 combustor, testing is conducted under several operating conditions to simulate relevant cold-start and altitude relight conditions. Table 1 lists the different operating conditions that are tested. Three temperature conditions are tested at near-ambient pressure conditions, simulating ground cold-start scenarios. Additionally, one condition is tested to simulate a low-altitude relight scenario.

Figure 2. The SmEARF high-altitude chamber at the Army Research Laboratory at Aberdeen Proving Ground, MD (left). The M1 combustor installed in the altitude chamber, ready for cold-start and altitude relight testing (right).

Table 1. Combustor operating conditions for baseline ignition testing.

	Cold-Start	Altitude Relight
Fuel	F-24	F-24
Air Temperature	25°C, -10°C, -35°C	-5°C
Fuel Temperature	25°C, -10°C, -35°C	-5°C
Total Air Flowrate	30 g/s, 31 g/s, 32 g/s	23 g/s
Combustor Absolute Pressure	92.5 kPa	69.4 kPa
Target Combustor Pressure Drop	3%	3%

Ignition Testing Procedure

To collect ignition probability measurements for each case, the following procedure was followed. An ignition attempt is started by directing chilled fuel into the combustor without sparks for 3 seconds to allow the fuel flowrate to stabilize at the desired value. After this period, DC power is supplied to the exciter, and the igniter is allowed to spark at a frequency of ~3.7 Hz for up to 10 seconds, at which point the sparks and fuel flow are stopped. Upon successful ignition of the combustor, the test is considered complete, and the fuel and sparks may be stopped early. An analysis script uses the recorded photodiode signal to measure the emission from the sparks and the flame to determine which spark resulted in successful ignition. Based on this process, a maximum of one successful spark can be found in each ignition attempt. Figure 3 shows an example photodiode signal collected during an ignition attempt. After each ignition attempt, air is allowed to flow through the combustor for at least 2 minutes to clear out any remaining liquid fuel inside the combustor before the next test begins. This procedure is repeated many times at fuel flowrates across the ignition probability curve to ascertain the overall ignition behavior, ranging from no-ignition cases to the maximum reasonable fuel flowrate for the testing conditions.

Ignition probability curves are determined from the recorded datasets by first analyzing all tests runs and determining the number of successful and unsuccessful sparks in each test. The actual air and fuel flowrates from each test are also calculated from the recorded data to obtain the exact equivalence ratio for each test run. The data are then split into equally sized bins based on the equivalence ratio, and the total number of unsuccessful and successful sparks is used to calculate the overall ignition probability for each bin. It is important to note that in this test procedure, it is assumed that each spark event is independent of all other events, which may not always be the case. While this assumption may not hold due to fuel accumulation in the combustor or slight variations in flowrates throughout the test runs, every effort is made to maintain these parameters to ensure that all test points can be considered independent.

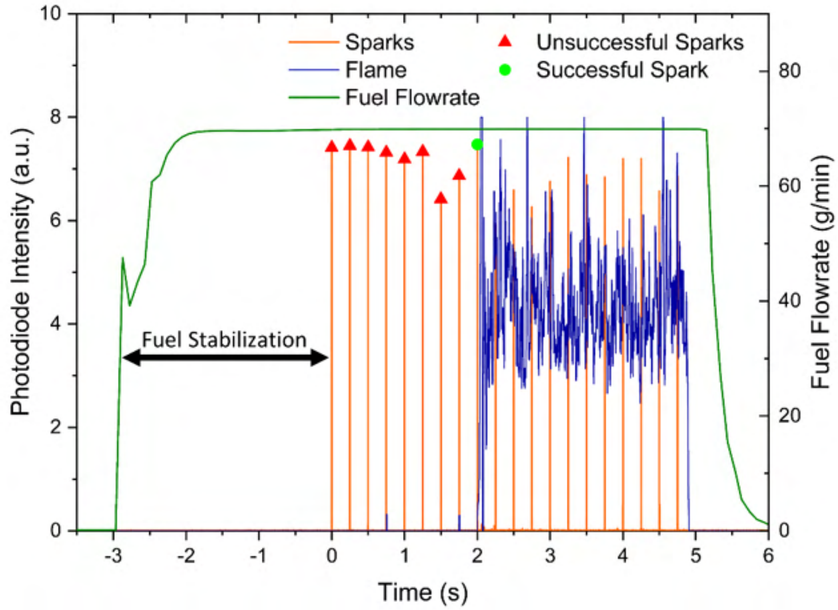

Figure 3. Example of the ignition testing procedure, demonstrating the fuel stabilization time and analyzed photodiode signals.

Ignition Performance Results

To collect baseline ignition performance data for the ARC-M1 combustor, the ignition measurement procedure described above was performed many times across a wide range of equivalence ratios for the three cold-start scenarios listed in Table 1. Figure 4 shows results from these measurements and binomial fits of ignition probability (fitted using data up to the maximum ignition probability). These results demonstrate the impact of reducing the combustor inlet temperature on combustor ignition performance. The highest temperature conditions demonstrate a very rapid transition from a zero ignition probability (no ignitions) to a very high ignition probability (consistent ignition on an early spark). For the middle temperature condition (-10°C), a much slower rise to high ignition probabilities is observed, likely due to the more difficult process of vaporizing and starting combustion in a lower-temperature environment. It is likely that combustion is still possible under these conditions, but the correct balance between liquid spray behavior, turbulent fluctuations in the combustor, and spark propagation is required for successful ignition. Additionally, in this middle temperature case, for higher equivalence ratio conditions, beyond the maximum ignition probability, a decrease in the ignition probability is observed. It is hypothesized that this result is caused by the increased amount of cold fuel in the combustor, which can quench any high-temperature region created by the spark in a very short amount of time. This greater quantity of cold fuel reduces the likelihood that the flame will reach the point at which it releases more chemical power than it is losing to the surrounding gases and increases the likelihood that the flame will blow out. For the lowest-temperature case, only a very narrow range of equivalence ratios allows ignition, and the ignition probabilities never rise to high levels (maximum of ~10%). The effects seen for the middle temperature condition are even more extreme here, with the -35°C air and fuel requiring significantly more energy to heat up to reaction temperatures, making it much less likely that a spark will make it all the way to a sustained flame without blowout occurring. These results provide a good baseline for ignition performance under cold-start conditions in the ARC-M1 combustor and illustrate how varying inlet temperature conditions impacts global ignition performance.

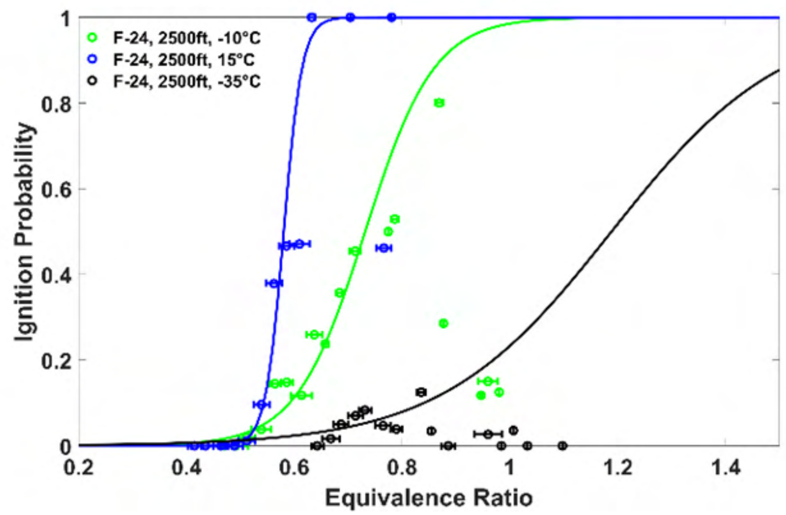

Figure 4. Baseline ARC-M1 ignition performance data collected under near-ambient pressure conditions in the SmEARF altitude chamber.

Figure 5 shows results of ignition testing on the ARC-M1 combustor performed under altitude relight conditions. Although the temperature conditions are much more favorable than the -35˚C testing conditions shown in Figure 4, the results appear very similar. The lower ambient pressure conditions of this testing appear to inhibit successful ignition in a manner similar to that observed for the -35˚C testing above, with no equivalence ratio yielding ignition probabilities greater than 10%. However, the range of equivalence ratios for which ignition does occur is significantly higher than that in the above testing. It is hypothesized that ignition does not occur until this point due to the inherent balance between fuel flowrate, fuel pressure, and droplet size. The fuel nozzle needs a sufficiently high inlet pressure to allow for favorable atomization performance; however, this results in a relatively high fuel flowrate, especially for these low-pressure (low air density) conditions. As such, ignition probabilities over a relatively wide range of equivalence ratios show similar, extremely low ignition probabilities under altitude relight conditions.

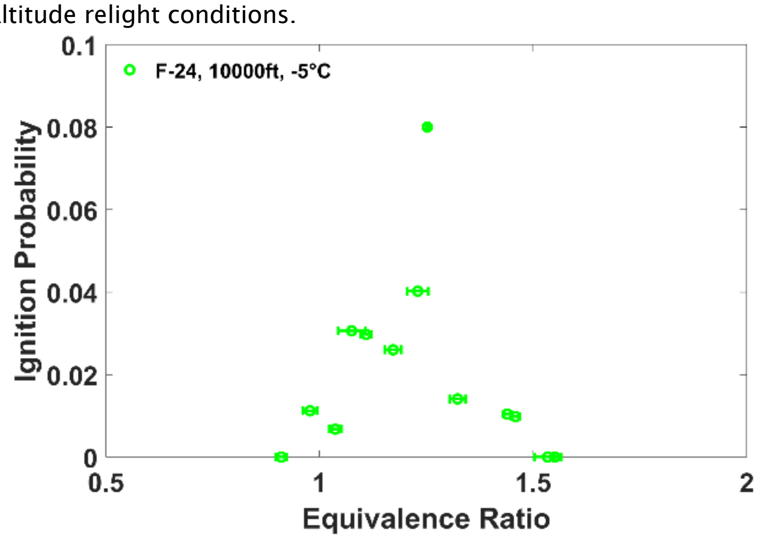

Figure 5. Altitude relight testing results (10,000-ft-equivalent conditions) for the M1 combustor in the SmEARF altitude chamber.

During the cold-start and altitude relight testing described above, high-speed broadband imaging was simultaneously collected to visualize the spark and the flame luminosity after the spark. The goal of this imaging was to investigate the link between flame trajectories in the time period immediately after the spark and successful ignition performance. Images were collected using a Photron SA-Z operating at 20,000 fps. Figure 6 shows images collected at several different time steps after the spark event for three unsuccessful sparks and one successful spark. This type of diagnostics provides an extremely powerful tool for identifying the high-speed dynamics governing these important phenomena. Future analysis of these images and the collection of additional diagnostics data will provide an even deeper understanding of the factors influencing successful ignition in gas turbine environments.

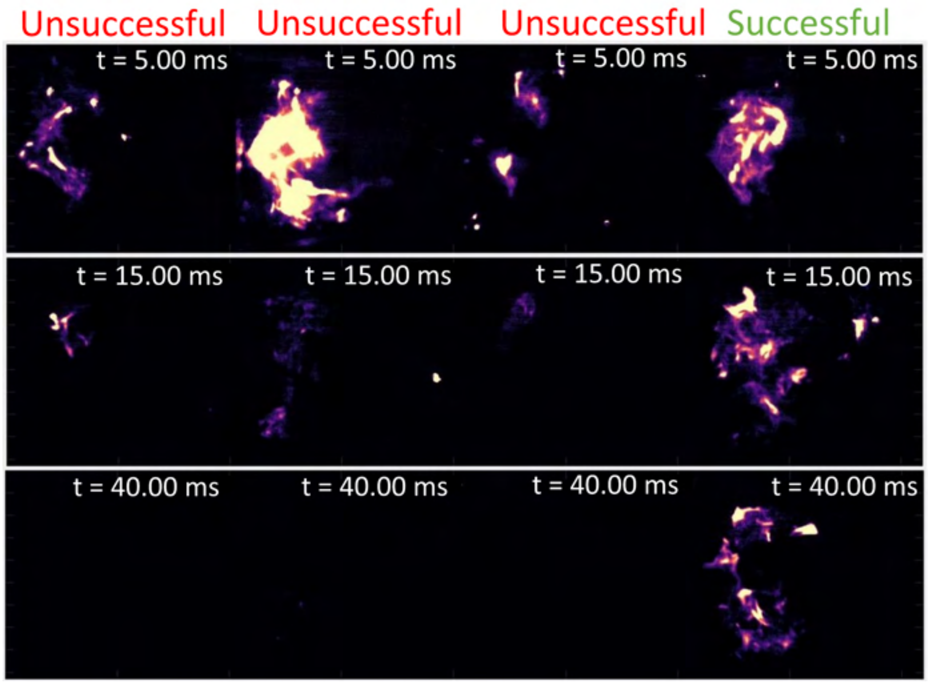

Figure 6. High-speed broadband image data from the M1 combustor during cold-start ignition testing.

These measurements represent initial baseline ignition testing in the M1 combustor and provide an important first step toward understanding the general combustor performance in the ignition regime in the M1 combustor. Further optimization of injection nozzles and test conditions will be needed. Combustor performance under ignition scenarios is a key performance metric to enable the introduction of SAF to the jet fuel supply pipeline. The M1 combustor is designed to enable a wide array of diagnostic techniques to study this phenomenon in more detail, including high-speed laser diagnostics such as PLIF and PIV, in addition to high-speed X-ray phase contrast imaging at ANL. Future efforts will apply these diagnostics of the M1 combustor to develop a deeper understanding of the physics leading to successful combustor ignition, in addition to providing an invaluable set of boundary conditions for combustor ignition simulation efforts. This work will provide the information necessary to determine whether small-scale combustors like the M1 can provide the data needed to inform large-scale programs aiming to integrate SAF on a wider level throughout the aviation industry.

Milestones

3 months: M1 combustor and control system setup and testing at UIUC.
6 months: High-altitude relight experiments at ARL (first attempt) – failed due to a fire in the facilities.
9 months: High-altitude relight experiments at ARL (second attempt) – successful.
12 months: Data analysis and identification.

Major Accomplishments

We have successfully collected baseline ignition performance data for the ARC-M1 combustor under cold-start and altitude relight operating conditions. We observed interesting phenomena for high-flowrate and low-temperature conditions, which we believe warrant further investigation using more advanced diagnostic techniques, such as X-ray phase contrast imaging. Additionally, the results from this testing suggest that it may be interesting to perform ignition testing on multiple nozzles to determine how nozzles with different droplet breakup behavior affect global ignition performance. These measurements will provide key information for identifying directions for future study to enable small-scale combustors to be used more widely as test platforms for SAF.

Publications

Wood, E., Motily, A., Trotter, C., Lee, T., Mayhew, E., Coburn, V., Temme, J., & Kweon, C. (2022). *Fuel spray and operating condition impact on ignition performance in the ARC-M1 combustor.* Conference paper in preparation.

Outreach Efforts

All test data will be made accessible through https://altjetfuels.illinois.edu/.

Awards

None

Student Involvement

This project was primarily conducted by one graduate student, Eric Wood (Ph.D.), and one undergraduate student, Caleb Trotter.

Plans for Next Period

A deeper investigation into the effects observed in our baseline testing will be conducted by using high-speed X-ray phase contrast imaging.

Task 2 – LBO Measurements for the M1 Combustor

Objective

The objective of this task is to conduct baseline lean blowout measurements for the M1 combustor, similar to those carried out in the referee combustor as part of the NJFCP. These measurements will indicate how this smaller standard combustor compares with the referee rig under similar test conditions.

Research Approach

Throughout the NJFCP, the referee combustor and several other combustors were carefully characterized under a variety of relevant operating regimes, including blowout and ignition. These studies were conducted under a range of standard operating conditions relevant to gas turbine operational regimes that are likely to expose differences between fuels with varying properties. While experiments in the referee combustor have provided valuable data regarding fuel effects near LBO, operating the referee rig comes with some disadvantages. The scale of the referee combustor brings large air and fuel flowrate requirements, which can make setup and operation expensive, especially for studies of new alternatively derived fuels, which may be difficult to manufacture. As such, it would be beneficial if similar results could be obtained from a smaller combustor with reduced fuel and air requirements. The M1 combustor uses significantly less air and fuel, reducing the overall instrumentation expense and complexity and reducing the volume of fuel needed to conduct tests over a range of conditions. With these advantages, the M1 combustor could be used to evaluate the performance of new fuels with much less fuel, reducing the supply requirements for a potential new fuel supplier. To achieve this goal, we must ensure that the trends observed in a smaller combustor can convey the physics observed in other test combustors, such as the referee combustor.

Lean Blowout Testing Procedures

Performing lean blowoff measurements on a combustor in a reliable and repeatable manner involves careful control of all combustor operating parameters, including the fuel flowrate, air flowrate, air temperature, and combustor pressure. To ensure that combustor conditions are stable before the lean blowoff test is conducted, the combustor is ignited at a fuel flowrate above the lean blowoff point, and combustion is sustained at that flowrate until the combustor wall temperature and air outlet temperature reach steady-state conditions. After steady-state temperatures are reached, the fuel flowrate is slowly reduced until blowout occurs. For these experiments, the fuel flowrate is reduced by approximately 0.025 g/min each second. This low ramp rate helps to ensure that the combustor wall temperature does not bias the lean blowoff point. This fuel ramp rate was chosen as a balance between ensuring a steady, repeatable approach to LBO and minimizing the total amount of fuel needed for the experiments. As the fuel flowrate is stepped down, all other combustor operating parameters are closely monitored to ensure that they stay within the specified parameter range. The specific lean blowoff point is monitored by recording a photodiode signal simultaneously with all other combustor parameters at 10 Hz. The lean blowoff point is determined for each test by finding the equivalence ratio at the point where the photodiode signal indicates that blowoff has occurred. To reduce random variations in LBO from affecting the reported results, each test is conducted at least 20 times at each combustor condition. Operating conditions for these experiments have been chosen to facilitate comparison with previous experiments conducted in the NJFCP referee combustor. Table 2 includes the conditions tested for an initial comparison between four fuels under a single set of combustor conditions.

Table 2. Operating conditions for fuel comparison in the ARC-M1.

Fuels	F-24, C-1, C-3, C-5
Combustor Absolute Pressure (atm)	2.0
Main Air Flowrate (g/s)	55.3
Air Preheat Temperature (K)	394
Pressure Drop – ΔP/P (%)	3

Lean Blowout Results

Figure 7 shows LBO results from the M1 combustor for the selected reference conditions listed in Table 2 to compare the blowout behavior of fuels with varying properties in the relatively small M1 combustion environment. The results are normalized by the equivalence ratio for the reference jet fuel, F-24, and are presented against four fuel properties: the 20% distillation temperature (T20), 90% distillation temperature (T90), DCN, and kinematic viscosity. The error bars represent two standard deviations of the LBO equivalence ratio. These results show a strong correlation between LBO performance and T20 as well as the kinematic viscosity, while a weaker correlation is shown for T90. Meanwhile, there is no apparent dependence on the DCN, which is related to the fuel's chemical characteristics. While this finding does not match some of the DCN results shown in previous works on the larger referee combustor (not all referee combustor results had a DCN correlation), previous work on the M1 combustor has shown significant differences in near-nozzle droplet sizes between these fuels while operating under similar combustor conditions. Meanwhile, droplet sizes, measured inside the referee combustor for several tested fuels, were relatively similar between the fuels. As such, the LBO performance in the M1 combustor appears to be dominated by fuel atomization behavior (linked to kinematic viscosity) and initial vaporization of the fuel. The relatively lower dependence on T50 (not pictured) and T90 demonstrates that the ability to vaporize the initial 20% of the fuel determines the overall LBO performance of the combustor under these conditions. This observation of LBO performance also suggests that preferential vaporization effects are important to LBO behavior in small-scale combustors such as the ARC-M1, an aspect that warrants further investigation. Additionally, it is acknowledged that there is often a correlation between fuel distillation temperatures and kinematic viscosity; thus, one of these factors may be far more dominant than the other, presenting another consideration that must be investigated further in future work.

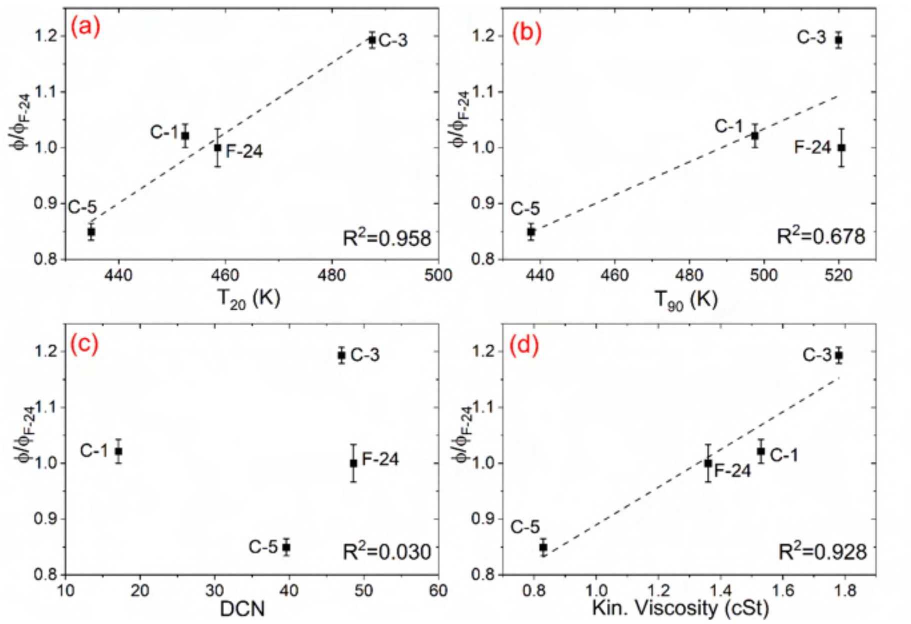

Figure 7. LBO results for the ARC-M1: T20 (a), T90 (b), DCN (c), and kinematic viscosity (d). Combustor conditions for this data are included in Table 2. Error bars represent two standard deviations.

These results demonstrate a strong dependence on fuel properties governing atomization and vaporization, in contrast to many of the results shown for the referee combustor in the NJFCP, which raises the important question of whether the fuel nozzle used for all of these baseline measurements is appropriately sized for the smaller combustor size of the M1 combustor, as compared with the much larger referee combustor. The clear dependence of lean blowoff performance on parameters governing fuel atomization and vaporization suggests that the existing nozzle may produce droplets that are far too large to be vaporized and combusted within the length scales of the smaller M1 combustor and that a new, smaller nozzle may be necessary to capture the physics that are dominant in larger combustors, which are more representative of those used in currently operating aircraft. As such, in the upcoming months, testing will be conducted on a range of new fuel nozzles, which should offer significantly improved fuel atomization performance compared with the existing nozzle, which may shift the operating regime of the M1 combustor to the chemically dominated regime as compared to the physically dominated regime in which it is currently operating. Figure 8 presents a photograph of some of the new fuel nozzles (with smaller fuel droplet sizes) that will be tested in the near future.

Figure 8. New nozzles being tested in the ARC-M1 combustor to evaluate ignition performance.

Milestone(s)

6 months: M1 combustor setup, shake-down, and selection of LBO test conditions.
9 months: Preliminary data collection for LBO in the M1 combustor for select fuels.

12 months: Comparison of lean blowout measurements for select NJFCP fuels in the M1 combustor with referee combustor data.

Major Accomplishments

We have conducted a baseline LBO measurement in the M1 combustor for comparison with the referee combustor using key NJFCP fuels. The results show an overwhelming dependence on the physical properties of the fuels, and new efforts to optimize a nozzle with lower flowrates (and a higher degree of atomization) will be implemented in the near future.

Publications

Wood, E., Motily, A., Trotter, C., Lee, T., Mayhew, E., Coburn, V., Temme, J., & Kweon, C. (2022). *Fuel spray and operating condition impact on ignition performance in the ARC-M1 combustor*. Conference paper in preparation.

Outreach Efforts

All test data will be made accessible through https://altjetfuels.illinois.edu/.

Awards

None

Student Involvement

This project will be primarily conducted by two students: Eric Wood (Ph.D.) and Caleb Trotter (undergraduate).

Plans for Next Period

New injectors with smaller atomization droplet sizes will be optimized for the M1 combustor to ensure that the chemistry aspect of the fuel is properly reflected in the overall combustor performance. This effort will require new imaging of the droplet sizes at the ANL's Advanced Photon Source to acquire initial conditions for numerical simulations, as the droplet sizes will change.