Project 027(A) National Jet Fuels Combustion Program – Area #3: Advanced Combustion Tests (Year III)

Georgia Institute of Technology, Oregon State University, University of Illinois[3]

*this report covers portion of University of Illinois

Project Lead Investigator

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University Participants

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- P.I.(s): Tonghun Lee, Associate Professor
- FAA Award Number: 13-C-AJFE-UI-016
- Period of Performance: 10/1/2016 to 9/30/2017
- Task(s):
    1. Conduct high altitude relight ignition probability measurements in the modified sector rig at ARL.
    2. Conduct ignition delay measurements of the targeted cetane number fuels in the RCM at UIUC.

Project Funding Level

Funding Level: $200,000
Cost Share: In-kind academic time of the PI, cost share provided by software support from Convergent Sciences Inc.

Investigation Team

- Eric Mayhew (Graduate Student, University of Illinois at Urbana-Champaign): Execution of laser and optical diagnostics at ARL.
- Kyungwook Min (Graduate Student, University of Illinois at Urbana-Champaign): Rapid Compression Machine testing of fuels.
- Brendan McGann (Graduate Student, University of Illinois at Urbana-Champaign): Execution of laser and optical diagnostics at ARL.
- Constandinos Mitsingas (Graduate Student, University of Illinois at Urbana-Champaign): Execution of laser and optical diagnostics at ARL.

Project Overview

The objective of this project is to support measurements of ignition probability at high altitude conditions and fundamental ignition delay measurements as a part of the FAA COE ASCENT's combustion program. The effort will strive to meet two critical targets. The first is to make measurements of ignition probabilities of jet fuels at altitudes between 10,000 and 30,000 ft. in a sector rig with key geometry matching the NJFCP referee rig at Wright-Patterson Air Force Base. The second goal is to make measurements of ignition delay for targeted cetane number fuels in a rapid compression machine at UIUC to enhance our understanding of the importance of cetane number in low-temperature autoignition experiments and how it relates to lean blowout (strongest correlating parameter to lean blowout). The success of this program will substantially accelerate the efforts of the FAA and the OEMs to certify alternative, fit for purpose fuels.

Task #1: Measure Ignition Probability for Various Fuels at High Altitude Conditions and Implement High-Speed Imaging to Visualize Ignition Process

University of Illinois at Urbana-Champaign

Objective(s)

The objectives in this project are to work with ARL in the design, setup, and implementation of ignition experiments in the high-altitude chamber at Army Research Laboratory at Aberdeen Proving Ground:

- Design and set up sector rig in high altitude chamber at Army Research Laboratory at Aberdeen Proving Ground.
- Conduct measurements of ignition probability at high altitude conditions (low temperature, low pressure).
- Implement high-repetition rate broadband and OH* imaging to visualize ignition kernel and flame kernel propagation.

Research Approach

The process of developing and approving new jet fuels derived from alternative feedstocks requires certifying that those fuels, whether neat or blended with conventional fuels, can be used in current engines without hardware modification. Understanding how these new fuels perform in extreme combustion regimes is important to ensuring that the fuels can be used as drop-in replacements. One regime in which it is essential that new fuels perform as well as conventional fuels is in a scenario where an engine needs to be relit at high altitude. The lower temperatures and pressures seen at high altitudes result in a lower probability of spark kernel ignition and flame stabilization when compared to sea level conditions. A few of the causes of this reduced probability include slower chemistry, poorer atomization due to the higher fuel viscosity, slower evaporation due to the reduced vapor pressure of the fuel, and shorter spark kernel lifetime due to the entrainment of the lower temperature air. To study the effects of fuel differences in this high altitude relight scenario, a gas turbine combustor sector rig was designed and built. The sector rig is operated inside of a high-altitude chamber with the chamber conditions varying as shown in Table 1, with 30,000 ft being the highest altitude that the chamber is capable of simulating.

Table 1 Chamber air temperature and pressure as a function of altitude

Altitude (ft)	T_{air} (K)	P_{air} (kPa)
0	288	101.3
10,000	268	69.6
20,000	249	46.6
25,000	239	37.7
30,000	229	30.2

Ignition probabilities for alternative and conventional jet fuels are measured in a gas turbine sector rig inside of a high-altitude chamber as shown in Figure 1. Experiments are designed to simulate combustor relight at high altitude conditions. Initial relight experiments were conducted at conditions representative of ambient air at 10,000 feet with an air mass flow rate of 0.3lbm/s. This air flow mass flow rate resulted in a pressure drop across the swirler of 3.87%. The fuel is chilled by placing the fuel holding vessel in the inlet air flow path, resulting in an average fuel injection temperature of -15˚C. The equivalence ratio is varied by changing the inlet fuel pressure, and fuel flow rates could be varied to achieve equivalence ratios from 0.6 and 1.0. This range of equivalence ratios was sufficient to span from no ignition to always igniting.

A single test begins with the opening of a solenoid valve just upstream of the nozzle, allowing fuel flow at the desired equivalence ratio. After two seconds in which the fuel flow rate is allowed to stabilize, a 24 VDC voltage is supplied to an ignition exciter (Champion CH305050), which supplies high voltage to an igniter from a General Electric T700 at a frequency of 3.7 Hz. The igniter is allowed to spark for 10 seconds, after which the voltage and fuel supply are stopped. The sparks and flame are monitored with a photo diode as well as a high-speed camera (Photron SA-Z) coupled to a high-speed intensifier (LaVision IRO), fitted with a bandpass filter centered at 320 nm, with a full-width, half-max of 20 nm. A sample photodiode trace is shown in Figure 3. The spark emission events are shown as the sharp peaks, and the flame is observed as the slight increase in photodiode signal above the baseline between the sharp peaks.

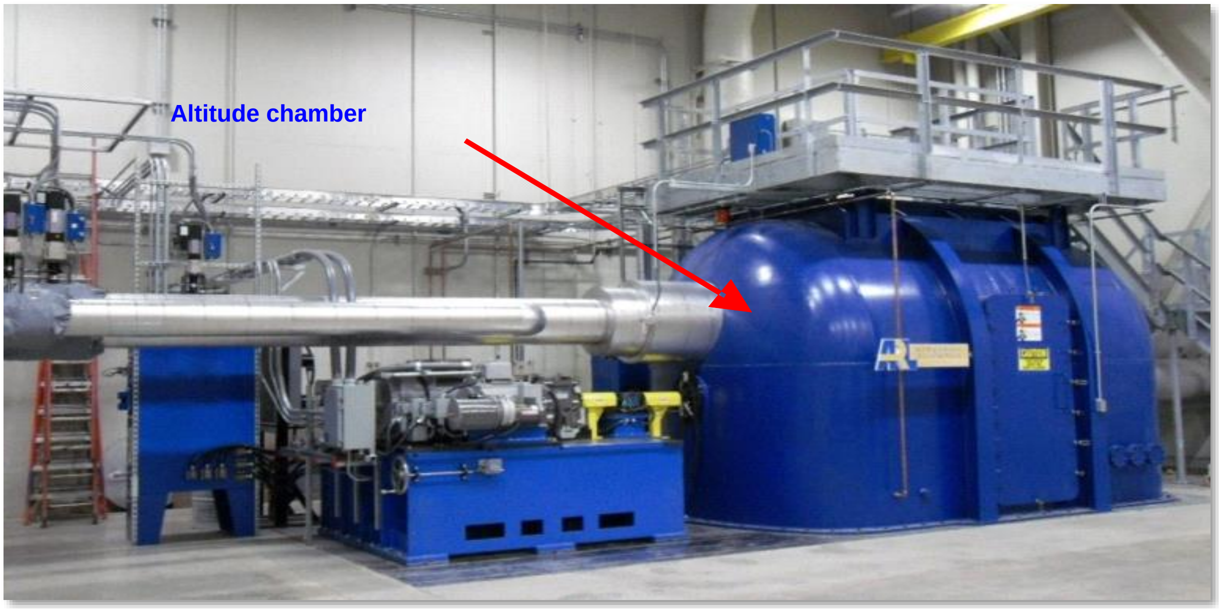

Figure 1 High altitude chamber at the Army Research Laboratory at Aberdeen Proving Ground

A total of 5 fuels were tested, all from the National Jet Fuel Combustion Program. Three conventional fuels, designated A-1 (JP-8), A-2 (Jet A), and A-3 (JP-5), represent current petroleum-derived fuels that are used in modern aircraft engines. Two category C fuels were tested as well, designated C-1 and C-3. The C-1 fuel is Gevo alcohol-to-jet; its notable properties are a low derived cetane number (~16) and a relatively low temperature boiling curve. C-3 is notable for its high viscosity, a parameter that is particularly important for atomization at these low temperatures.

For each test, a photo diode trace like the one shown in Figure 3 is obtained. A flame is considered to have stabilized when the ratio of the absolute value of the integrated negative signal to the integrated positive signal is less than 1% for two consecutive periods between sparks. The number of sparks that do not result in a stable flame are counted along with the one spark that resulted in the stable flame. The ignition probability for a single equivalence ratio for a single fuel is the number of successful sparks divided by the total number of sparks. The ignition probability for all of the fuels and equivalence ratios tested are shown in Figure 1 as well as the binomial regression fits calculated from the ignition probabilities. Defining the 'best' fuel case as the fuel that has the highest ignition probability for each equivalence ratio, the preliminary analysis yielded a fuel ordering, from best to worst of: A-1, C-1, A-2 and A-3 about equal, and then C-3. More complete analysis of the images and ignition probabilities is ongoing; however, the parameters that appear to be most important in determining ignition probability are viscosity and vapor pressure at the temperatures measured in the rig. Further analysis of the video will provide a better qualitative understanding of the process in which a spark kernel leads to a flame kernel, eventually resulting in stabilization of the flame in the combustor. Further testing is required and planned to obtain lower uncertainties in the probability curves as well as to obtain data for more fuels and at more altitudes.

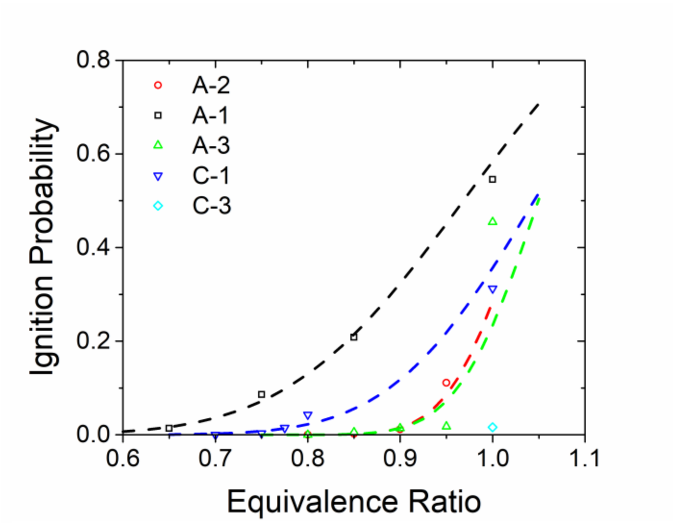

Figure 2 Ignition Probability versus equivalence ratio for the 3 category A fuels and 2 category C fuels at 10,000 ft.

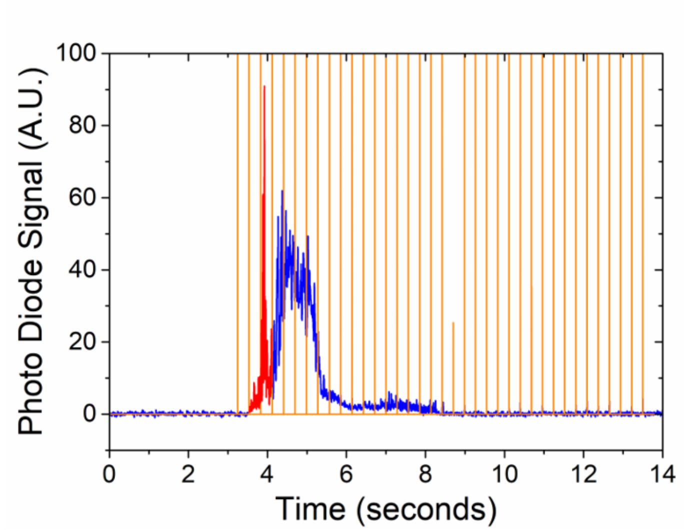

Figure 3 Example photodiode trace of sparks and a successful ignition

Task #2: Measure Ignition Delay at Low Temperature Conditions for Fuels with Targeted Cetane Numbers

University of Illinois at Urbana-Champaign

Objective(s)

The objectives in this project are to make measurements of ignition delay of targeted cetane number fuels developed by ARL cetane number has shown a strong correlation to lean blow out equivalence ratio.

Varied cetane number army research fuels

Six different fuels have been tested to measure the ignition delay time in the RCM. These fuels are blended to match a targeted cetane number between 30 and 55. CN 50 appears to be the base fuel used prior to the inclusion of cetane inhibitors /improvers. Isododecane (pentamethylheptane) is used as the cetane inhibitor, as well as naphthalene in the CN 30. Inclusion of higher n-alkanes (C14 - C16) is used as the cetane improver for CN 55. Navy Fuel Composition and Screening Tool (FCAST) have been used to classify detailed chemical group composition of the fuels as in Table 2. Contents of isoalkanes and aromatics are higher for low cetane number fuels, whereas higher cetane number fuels tend to contain more normal alkanes.

Table 2 Compisition of the Army research fuels tested

mass %	Jet A-30CN	Jet A-35CN	Jet A-40CN	Jet A-45CN	Jet A-50CN	Jet A-55CN
Normal Alkanes	16.02	16.48	21.83	19.54	36.50	54.10
Isoalkanes	54.80	58.22	41.41	48.14	34.14	28.33
Cyclocalkanes	3.85	1.21	3.22	10.94	12.18	6.08
Aromatics	25.32	24.08	33.53	21.41	17.18	11.46

Ignition delay of varied cetane number fuels

Ignition delay time measurements have been conducted for compressed pressures of P_c=20 bar, at equivalence ratios (φ) of 1.0, 0.5, and 0.25. Compressed temperature T_c varies by compression ratio: 615K to 725K. Figure 4 shows measured ignition delay time at P_c=20 bar.

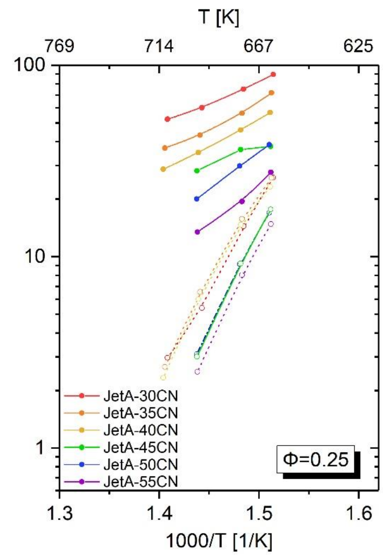

Figure 4 First and overall ignition delay time results at φ=0.25

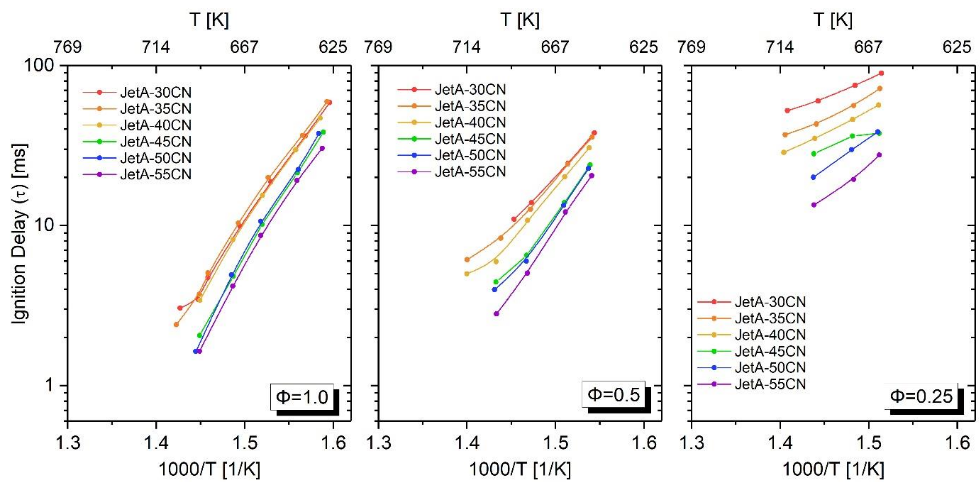

Figure 5 Ignition delay times of Jet A fuels with varied cetane numbers at Pc=20 bar, varied temperatures, and equivalence ratios

As expected, fuel with lower cetane number results in longer ignition delay, and the tendency is more prominent at leaner conditions. In the φ=1 case, some of the ignition delay time results do not exactly follow the cetane number ordering. No negative temperature coefficient (NTC) behavior is observed in these tests. Further analysis of the φ=0.25 case is illustrated in Figure 5, where dotted lines are separated first stage ignition delay time. The difference in first stage ignition delay time by fuels are much less than difference in overall ignition delay time. In other words, the second stage ignition delay constitutes nearly all of the differences in the overall delay time. Additional ignition delay time measurements will be conducted at lower compressed pressure, P_c=10 bar. Further analysis on multistage ignition will be investigated using CHEMKIN, chemical kinetics simulation results.

Milestones

Proposed (3 Month): At the 3 month mark, we should have shipped the sector rig to ARL to begin setting it up in the high altitude chamber.
Achieved: Army Research Combustor-L1 shipped to ARL, and preparations for high altitude relight campaign have begun.

Proposed (6 Month): At the 6 month mark, we should have purchased peripheral components for the high altitude relight campaign, and a test matrix should have been decided on.
Achieved: The designs have been finalized and drawings sent to the machine shop. Materials for the rig have been ordered.

Proposed (9 Month): At the 9 month mark, we should have completed the high altitude ignition probability test matrix set out in the previous period. The ignition delay measurements in the RCM should have been completed.
Achieved: High altitude relight measurements at 10,000 ft, and hardware upgrades for future campaigns have been planned. Ignition delay measurements have been completed.

Proposed (12 Month): At the 12 month mark, we should have finished analyzing the ignition probability data and RCM ignition delay data.
Achieved: Preliminary analysis of the ignition probability data and RCM data has been completed

Major Accomplishments

High Altitude Relight Combustor
Design and fabrication of a high altitude relight rig, replicating the key geometry and flow features of the referee rig has been completed. The sector rig was set up in the high-altitude chamber, and modifications to the chamber and fuel delivery system were made. Measurements of ignition probability for 5 fuels across a range of equivalence ratios at ambient pressure and temperature conditions that correspond to 10,000 ft. Further data is needed at higher altitudes to gain a better understanding of the fuel properties that drive ignition behavior at these conditions.

Target Cetane Number Ignition Delays
Ignition delay measurements for targeted cetane number fuels, with cetane numbers varying from 30 to 55, were made in a rapid compression machine at the University of Illinois at Urbana-Champaign. Higher cetane number correlated strongly with shorter ignition delay at low temperature. The results warrant further investigation into the targeted cetane number fuels in the NTC region to gain a better understanding of how the cetane number drives autoignition delay time in this regime.

Publications
E. Mayhew, C. Mitsingas, B. McGann, T. Lee, T. Hendershott, S. Stouffer, P. Wrzesinski, A. Caswell, Spray Characteristics and Flame Structure of Jet A and Alternative Jet Fuels, AIAA SciTech, AIAA-2017-0148, 2017

I. Chterev, N. Rock, H. Ek, B. Emerson, J. Seitzman, T. Lieuwen, D. Noble, E. Mayhew, T. Lee, Simultaneous High Speed (5 kHz) Fuel-PLIE, OH-PLIF and Stereo PIV Imaging of Pressurized Swirl-Stabilized Flames using Liquid Fuels, AIAA SciTech, AIAA-2017-0152, 2017

Outreach Efforts
None

Awards
I. Chterev, N. Rock, H. Ek, B. Emerson, J. Seitzman, T. Lieuwen, D. Noble, E. Mayhew, T. Lee, Simultaneous High Speed (5 kHz) Fuel-PLIE, OH-PLIF and Stereo PIV Imaging of Pressurized Swirl-Stabilized Flames using Liquid Fuels, AIAA SciTech, AIAA-2017-0152, 2017
(winner of the ***The Walter R. Lempert Student Paper Award in Diagnostics for Fluid Mechanics, Plasma Physics, and Energy Transfer***)

Student Involvement
Four graduate students (listed above) have participated in this project on a rotational basis to address various aspects of the project. Two students (Brendan McGann, and Eric Mayhew) made trips to ARL to deliver and set up the Army Research Combustor-L1 in preparation for the high altitude experiments. Three students executed (Brendan McGann, Constandinos Mitsingas, and Eric Mayhew) set up and executed the high altitude relight experiments outlined in Task 1. Kyungwook Min conducted the ignition delay measurements in RCM at UIUC.

Plans for Next Period
In year IV of the NJFCP, the main focus of our efforts will be to continue the execution of high altitude ignition experiments at the Army Research laboratory. The test conditions will be worked out with OEM input based on the data already collected, and the work will also be coordinated with the ongoing ignition work at GATech. We will continue to support AFRL in any diagnostics efforts required in the referee rig combustor. Looking into the future, we anticipate either PIV or PDPA measurements will be required in the sector rig a ARL to obtain flow field information. We have already designed the required hardware for this effort and will look for an opportunity to implement them with support from ARL and AFRL.