Project 034 National Jet Fuels Combustion Program – Area #7: Overall Program Integration and Analysis

University of Dayton

Project Lead Investigator

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University Participants

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- PI: Joshua Heyne
- FAA Award Number: 13-C-AJFE-UD (Amendment Nos. 9, 10, 13, 17, 18, and 24)
- Period of Performance: October 1, 2019 to September 30, 2020
- Tasks:
    1. Overall National Jet Fuels Combustion Program (NJFCP) integration and coordination.
    2. Investigation of chemical and physical effects on lean blowout (LBO).

Project Funding Level

Amendment No. 9: $134,999 (September 18, 2015, to February 28, 2017)
Amendment No. 10: $249,330 (July 7, 2016, to December 31, 2017)
Amendment No. 13: $386,035 (August 30, 2016, to December 31, 2017)
Amendment No. 17: $192,997 (August 3, 2017, to September 30, 2018)
Amendment No. 18: $374,978 (December 7, 2017, to December 31, 2018)
Amendment No. 24: $374,978 (February 5, 2020, to February 4, 2022)

Investigation Team

- Joshua Heyne (University of Dayton) is the project lead investigator for coordinating all NJFCP teams (both ASCENT and non-ASCENT efforts).
- Jen Colborn (University of Dayton) is a graduate research student assistant aiding in the testing of fuels on the Referee Combustor rig.
- Katherine Opacich (University of Dayton) is a graduate research assistant working to document NJFCP activities and analyze ignition data across NJFCP teams.
- Zhibin Yang (University of Dayton) is a graduate student research assistant working to develop jet fuel blend optimizer (JudO).

Project Overview

The NJFCP is composed of more than two dozen member institutions contributing information and data, including expert advice from gas turbine original equipment manufacturers (OEMs), federal agencies, other ASCENT universities, and corroborating experiments at the German Aerospace Center (DLR Germany), National Research Council Canada, and other international partners. The project is tasked to coordinate and integrate research among these diverse program stakeholders and academic PIs; cross-analyze results from other NJFCP areas; collect data for modeling and fuel comparison purposes in

a well-stirred reactor; conduct large eddy simulations of sprays for the Area 3 high-shear rig; procure additional swirler geometries for the NJFCP areas and allied partners while developing an interface of NJFCP modeling capabilities with OEM requirements. Work under this program consists of, but is not limited to:

- conducting meetings with member institutions to facilitate the consistency of testing and modeling,
- coordinating timely completion of program milestones,
- documenting results and procedures,
- creating documents critical for program process (e.g., fuel down selection criteria),
- soliciting and incorporate program feedback from OEMs,
- reporting and presenting on behalf of the NJFCP at meetings and technical conferences,
- integrating state-of-the-art combustion and spray models into user-defined-functions (UDFs), and
- advising the program steering committee.

Task 1 – Integration and Coordination of NJFCP Teams

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Objective

The objective of this Task is to integrate and coordinate all ASCENT and non-ASCENT team efforts by facilitating meetings, summarizing results, presenting results external to the NJFCP, communicating regularly with the steering committee, and other related activities.

Research Approach

The NJFCP is integrated and coordinated by two main techniques: (1) the structural combining of various teams into six topic areas, and (2) routine meetings and discussion both internal and external to individual topic areas. The topic areas are distinguished by the dominant physics associated with them (topics I and IV), the culmination of all relevant combustion physics (topics II, III, and V), and wrapping all work into a singular OEM graphical user interface package (topic VI). These six topic areas are as follows:

Topic I. Chemical kinetics: Foundational to any combustion model is a chemical kinetic model and the validation data anchoring modeling predictions.
Topic II. LBO: This topic covers data, screening, and validation under relevant conditions to statistically and theoretically anticipate fuel property effects on this figure of merit (FOM).
Topic III. Ignition: Similar to the LBO topic, the focus here is experimental screening and validation data for statistical and theoretical predictions.
Topic IV. Sprays: Historically, the dominant effect of fuel FOM behavior has been the spray character of the fuel relative to others. Experimentalists in this topic area focus on measuring effects of fuel property on spray behavior. Analogous to topic I, spray behavior is not an FOM like topics II and III, although it is critical to bound the physical property effects on combustion behavior relative to other processes (i.e., chemical kinetics).
Topic V. Computational fluid dynamics (CFD) modeling. Complementary to the empirical topics II, III, and IV, the CFD modeling topic focuses on the theoretical prediction of measured data and facilitates the development of theoretical modeling approaches.
Topic VI. UDF development: Once the theoretical modeling approaches matured in topic V are validated, UDFs are developed for OEM evaluation of fuel performance in proprietary rigs.

These topic area teams meet and coordinate regularly. The coordination meetings have been reduced in the current reporting period.

Milestones

NJFCP AIAA Book.
Developed Tier Alpha prescreening tool for novel sustainable aviation fuel (SAF) prescreening.

Major Accomplishments

- Book editing and coordination.

- Developing and publishing a Commercial Aviation Alternative Fuels Initiative (CAAFI) R&D prescreening document to provide guidance to novel companies and producers in the refinement and development of fuels to facilitate reduced testing in later stages.

Publications

Peer-reviewed journal publications

Colborn JG, Heyne JS, Stouffer SD, Hendershott TH, Corporan E. Chemical and physical effects on lean blowout in a swirl-stabilized single-cup combustor. Proc Combust Inst 2020. doi:10.1016/j.proci.2020.06.119.

Published conference proceedings

None

Outreach Efforts

Invited talks

Heyne, J. (2020). Prescreening of sustainable aviation fuels. ACS Fall 2020 National Meeting & Exposition, San Francisco, CA

Conference presentations

Yang Z, Heyne J, Ave P, States U. A GCxGC Tier Alpha and Combustor Figure-of-Merit Approach on Sustainable Aviation Fuels Prescreening 2018:1–6. Eastern States Section of the Combustion Institute. University of South Carolina

Awards

None

Student Involvement

Katherine Opacich, graduate research assistant, October 2019 to September 2020. Katherine is working on writing an ignition book chapter.
Jen Colborn, graduate research assistant, October 2019 to September 2020. Jen is working on writing an LBO book chapter.
Zhibin (Harrison) Yang, Ph.D. student, October 2019 to September 2020. Harrison is working on developing Tier Alpha prescreening tool.

Plans for Next Period

Finalize the AIAA book editing.

Task 2 – Investigation of Chemical and Physical Effects on LBO

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Objective

The objective of this Task is to investigate chemical and physical effects on LBO in a swirl-stabilized single-cup combustor.

Research Approach

Introduction

The lower stability limit of gas turbine engines, or lean blowout (LBO), is an important limit phenomenon for safety, the approval of novel sustainable aviation fuels, and identifying transitions between competing physics [1]. LBO is a complex process that can be impacted by engine design, operating conditions, or any number of fuel properties.

Combustor configuration strongly influences LBO limits. Recirculation zones, air velocity, and combustor dome pressure drop (ΔP) are all influenced by the combustor, nozzle, and swirler design. These different features can impact fuel spray and mixing quality. Nozzle atomization technique and cone angle have been found to influence the equivalence ratio at LBO (φ_{LBO}) [2,3]. The presence of a swirler, as well as the number of vanes, swirl angle, and swirl direction impact the spray quality which will influence φ_{LBO} [4–8].

Fuel properties have also been found to impact φ_{LBO} strongly. Lefebvre found that varying fuel atomization and evaporation properties strongly influenced φ_{LBO} in a variety of engine geometries [9]. Physical properties have been shown to strongly impact LBO due to their influence on atomization [9–12]. Fuel property variance can be found within petroleum-derived fuels, impacting LBO limits regardless of engine configuration [9,13].

Changes in operating conditions can also heavily influence φ_{LBO}. Variances in combustor pressure (P) and ΔP can lead to differences in air velocity, which can affect fuel atomization. Fuel and air temperatures highly influence evaporation as well as droplet breakup, since the physical properties that control fuel atomization are highly temperature dependent [3]. Increased temperatures cause less required energy from the combustion process to vaporize the fuel, leading to an improved LBO limit.

Aircraft engines must operate over a wide range of pressures and temperatures where LBO performance is important. Combustor conditions vary throughout flight, which can influence LBO limits. Fuels must be able to perform acceptably under these varying conditions. Lefebvre described φ_{LBO} with Eq. 1, where combustor design parameters, thermo-fluid effects, and fuel-dependent properties demonstrate the multi-property dependency of LBO [9].

$$\phi_{LBO} = \underbrace{\left[\frac{f_{pz}}{v_{pz}^{(1+x)}}\right]}_{Geometry} \underbrace{\left[\frac{\dot{m}_A^{(1+x)}}{p_3^{(1+nx)}\, exp(x\, T_3/b)}\right]}_{Thermofluids} \underbrace{\left[\frac{D_0^2}{\lambda_{eff} LHV}\right]}_{\substack{Fuel \\ Effects}} \tag{1}$$

Burger, Plee, and Mellor have extended the work of Lefebvre, evaluating LBO by considering the effects of chemical kinetics, operating conditions, and combustor geometry [14–16]. Through a combination of relevant fuel parameters and combustor geometries, the chemical, evaporative, and mixing timescales can represent autoignition and extinction, fuel volatility, and combustor properties, respectively, as shown in Eq. 2. Peiffer utilized this method to compare the variance of φ_{LBO} in experimental rigs with varying geometries and operating conditions to explain the relative importance of fuel properties [17]. Dependence on physical properties was noted in rigs without swirlers, which hinders atomization [18].

$$\phi_{LBO} \sim \left(\frac{1}{\tau_{chem}} + \frac{1}{\tau_{evap}} + \frac{1}{\tau_{mix}}\right)^{-1} \tag{2}$$

Recent LBO investigations have also shown high sensitivity to fuel properties [19,20]. A swirl-stabilized, single-cup combustor showed strong correlation to derived cetane number (DCN) at relatively high temperature and increased pressure conditions (T_{air} = 394K, T_{fuel} = 322K, P = 207kPa, ΔP/P = 3%) [19]. In contrast, Peiffer demonstrated that at relatively low temperatures and pressures physical properties, such as distillation temperatures and density were important for describing φ_{LBO} in an auxiliary power unit (APU) [17,18]. The difference in physical and chemical property dependence between different operating conditions implies competition between spray characteristics and autoignition stabilization.

While the extreme operational conditions detailed above demonstrated a difference in property importance, the transition between the physical and chemical regime has not been thoroughly investigated. This study seeks to investigate a transition from LBO performance physical property dependence (spray characteristics) to chemical property dependence (autoignition characteristics) with varying ΔP/P as well as air and fuel temperatures.

Test article

A swirl-stabilized single-cup combustor designed with turbine engine OEM input to simulate key characteristics of actual turbine engine combustors was used for LBO limit investigation (Figure 1). Referred to as the "Referee Combustor, it features effusion cooling and dilution holes as well as an injector and swirler that allow for the reproduction of important turbine engine combustor features [21]. The combustor is housed in a pressure vessel surrounded with fused silica windows to allow for optical access. The reduced combustor scale allows for ignition and LBO experiments with reduced fuel quantities for both elevated and cold fuel and air temperatures. Fuel impact assessments on these performance metrics in this combustor have shown similar trends to actual engines [19,21,22].

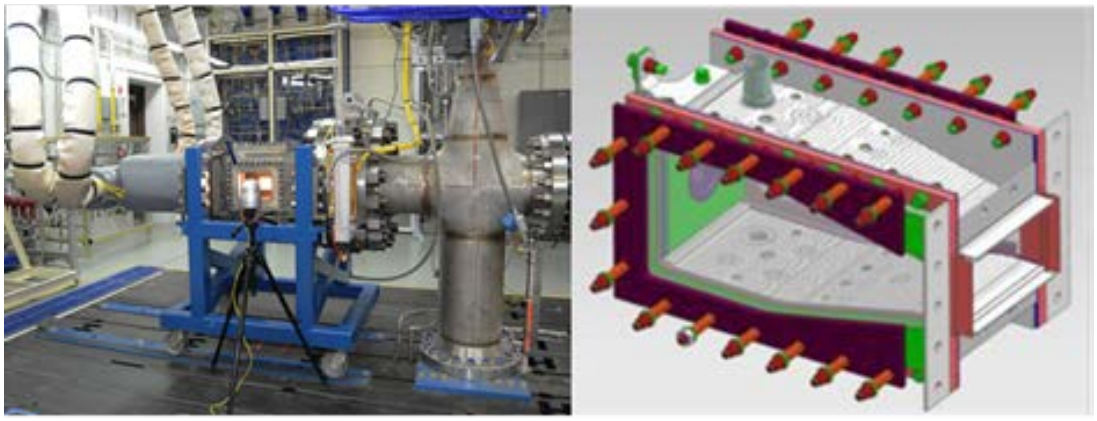

Figure 1. (a) Referee Combustor rig at the Air Force Research Laboratory (AFRL). (b) Swirl-stabilized (Referee) Combustor design.

Air mass flow to the combustor is metered using two Coriolis meters and pressure was regulated upstream of the control valves. Approximately 15% of the total air flow passes through the swirler, 22% through the dilution holes, and the other 63% through the effusion holes. The volume between the combustor dome and first stage dilution holes is 617 cm^3. Pressure transducers along the combustor wall measured ΔP at 15 Hz and a high-frequency response transducer at 150 kHz detected any pressure oscillations via semi-infinite tube technique. K-type thermocouples positioned on the outside of the combustor as well as the pressure vessel and surrounding supports allow for temperature monitoring to prevent structural damage. When required, fuel is heated using a heat exchanger with water supplied by a process fluid heater to deliver fuel at the nozzle at the desired fuel temperature. The fuel mass flow is measured using Coriolis meters upstream of the heat exchanger, before the nozzle. The fuel and air temperature were typically maintained within ±1.5K of the desired value. Two syringe pumps allow for fine control of the fuel flow.

Combustor LBO is very sensitive to fluctuations in the test conditions such as flow rate, pressure, temperature, and ΔP. Due to an emphasis on repeatability, control of these parameters was imperative. Proportional-Integral-Derivative (PID) loops were used extensively for fine control of various parameters. Pressure drop across the control valves was enough to choke the valves, keeping the mass flow supplied to the combustor independent of any downstream pressure fluctuations. In order to prevent fuel contamination from the previous test fuel, it was paramount to properly purge the fuel lines. Prior to each test, a fuel sample was collected near the fuel nozzle and tested for fuel purity via chemical analysis (GC-FID).

Experimental procedures

LBO tests were conducted by establishing pressure, air temperature, air mass flow, and ΔP. Fuel flow was then introduced and ignited. Adjustments were then made to the fuel temperature and flow rate until the desired condition was reached. After steady conditions were established within the combustor, the LBO test was initiated by slowly decreasing the fuel flow rate via syringe pumps at a rate of 0.25 mL/min every two seconds. For each condition, the LBO test was initiated from the same fuel mass flow rate, approximately 10% above the LBO limit. A slow ramp rate was important for achieving an unbiased LBO. Too fast a ramp rate may lead to a lower φ_{LBO} due to higher wall temperatures. Previous experiments determined that this rate allowed for a repeatable, smooth ramp, wall temperatures to adjust during experimentation, and maximized the number of experiments performed [19]. The LBO limit was determined by a rapid drop in the photodiode signal, which was directed at the primary combustion region. A sufficient number of LBO tests, usually between ten and fifteen, were conducted to ensure that agreement in values was achieved before moving to a different condition. Statistics were updated with each LBO test, and when the 95% confidence interval for the mean φ_{LBO} dropped below 0.75%, agreement was considered to be reached. This estimated φ_{LBO} was usually within a percent of the actual φ_{LBO} determined from more thorough post-test analysis of the 15 Hz photodiode signal. Experiments were performed at the conditions included in Table 1.

Table 1. Test Conditions Evaluated

P	$T_{air} = T_{fuel}$ [K]	ΔP/P [%]
107kPa	338	2,3,3.5,4,5, 6
	305,322,338, 355	3.5

Fuels

Four fuels were tested to study physical or chemical property influence (Table 2) on combustor LBO performance. The fuels were selected due to their wide range of physical and chemical properties. For reference, these were designated either A or C type fuels within the NJFCP [13]. A-type fuels are conventional petroleum fuels commercially available and C-type fuels are research fuels meant to highlight potential sensitivity to varying fuel properties.

Table 2. Fuels Evaluated and Corresponding Selected Physical and Chemical Properties Including 20 and 90% Recovered Temperatures (T_{20} and T_{90}, respectively, Molecular Weight (MW), and Lower Heating Value (LHV)

Property	ASTM Standard	A-2 Jet A	C-1 Alcohol-to-Jet	C-3 64% JP-5, 36% Farnesane	C-7 75% RP-2, 23% JP-5, 2% Decalin
DCN	D6890	48.3	17.1	47	42.6
Kinematic Viscosity, ν (253K, mm^2/s)	D445	4.5	4.9	8.3	6.53
Surface Tension, σ (295K, dynes/cm)	D1331	24.8	23.4	26.1	26.1
Density, ρ (288K, kg/m^3)	D4052	0.803	0.76	0.808	0.817
T_{20} (K)	D2887	447	445	478	464
T_{90} (K)	D2887	533	513	528	534
MW	n/a	159	178	180	170
LHV (MJ/kg)	D4809	43.06	43.8	42.39	43.3

A-2, a nominal Jet A with average properties, was selected as a baseline fuel. C-1 is an alcohol-to-jet, which features a very low DCN to test for chemical property dependence. To study physical property effects, C-3 was selected due to its high viscosity (ν). C-7 is a high cycloparaffin fuel (~62% cycloparaffins) with a high surface tension. Figure 2 displays the relative values of several physical and chemical properties for the tested fuels.

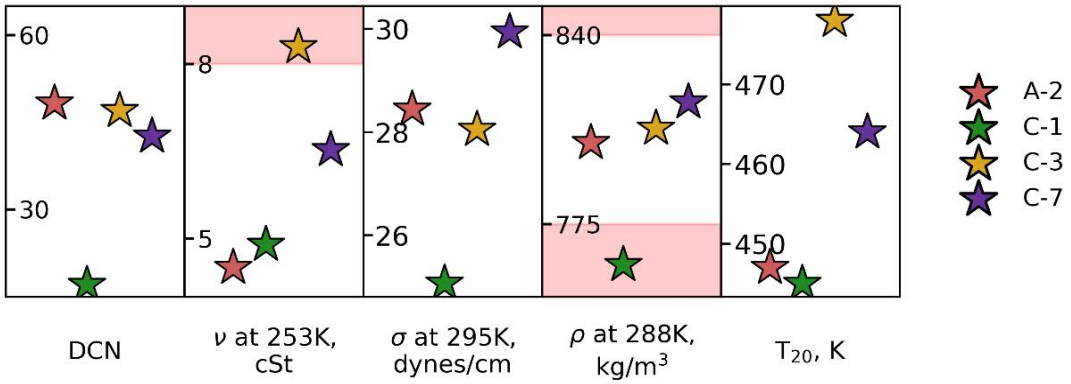

Figure 2 Physical and chemical properties of tested fuels. Red regions denote current specification limits.

Results and discussion

Combustor LBO performance is based on the φ_{LBO} as in previous studies [9,19,23]. The lower the φ_{LBO}, the less fuel is required to maintain the flame, indicating better LBO performance. Figure 3 shows φ_{LBO} response with varying ΔP/P and constant air and fuel temperature.

Increasing ΔP/P resulted in a non-monotonic φ_{LBO} ranking response across all fuels except C-3 were seen to collapse at 3.5% ΔP/P, at which point φ_{LBO} began to increase with increasing ΔP/P. As observed, the LBO limits for C-3 consistently decreased with increasing ΔP/P. Unfortunately, LBO tests for C-3 were not conducted at 6% ΔP/P due to heavy soot formation on the combustor liner and windows. At 2% ΔP/P, C-1 had the lowest (i.e., best) stability limit (φ_{LBO}) among fuels tested. In contrast, at ΔP/P=5 and 6% C-1 was observed to have the highest (i.e., worst) stability limit. The data for A-2 and C-7 diverge above 3.5% ΔP/P, below which they had almost identical performance.

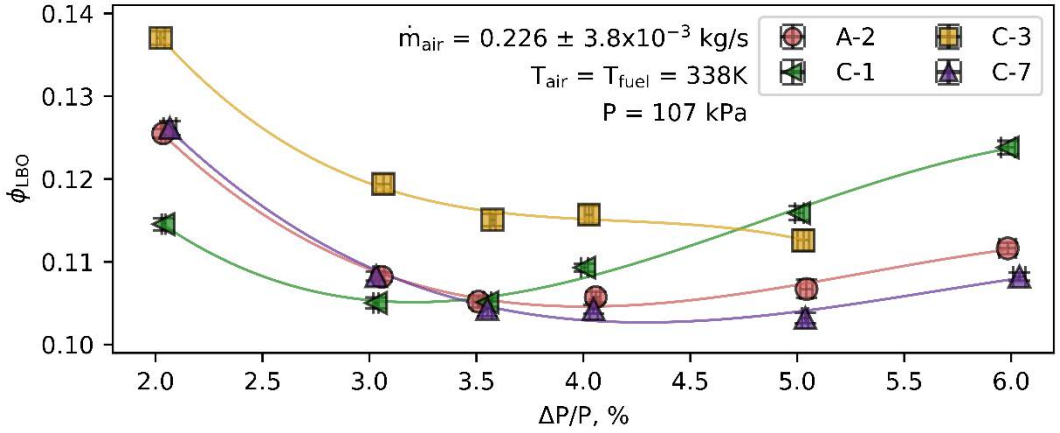

Figure 3. LBO limits (φ_{LBO}) as a function of combustor ΔP/P. Error bars denote the 95% confidence interval for φ_{LBO} and two standard deviations for ΔP/P.

At 2% ΔP/P, the LBO performance ordering of the fuels corresponded to physical property impacts. C-1, which possesses the lowest φ_{LBO}, had beneficial physical properties (lower surface tension, viscosity, and density) relative to other fuels, thus, promoting fuel atomization. Conversely, C-3 had less favorable physical properties (e.g., very high viscosity) which were detrimental to fuel atomization resulting in higher φ_{LBO}. The physical properties of A-2 and C-7 between the more extreme C-1 and C-3, resulting in φ_{LBO} between the two fuels. Low combustor ΔP/P consequently led to poor fuel atomization due to decreased aerodynamic forces acting upon the fuel droplets. With low aerodynamic forces, physical properties highly influenced fuel atomization and droplet size.

When considering the high ΔP/P cases of 5% and 6%, fuel performance changed dramatically compared to the 2% condition. At ΔP/P=5%, C-3 had a lower φ_{LBO} than C-1, which cannot be accounted for when only considering physical properties. C-1 had more favorable physical properties than C-3, which would result in better LBO performance if only physical properties were affecting LBO limits. It is clear that some other property or properties impacted fuel LBO performance at higher ΔP/P. In previous higher temperature and pressure studies (T_{air} = 394K, T_{fuel} = 322K, P = 207kPa, ΔP/P = 3%), DCN was identified as the dominant property for LBO performance due to its strong inverse correlation to φ_{LBO} [19,24,25]. The lower DCN of C-1 could account for its higher φ_{LBO} relative to C-3, indicating that chemical properties were beginning to impact φ_{LBO}. Once ΔP/P was high enough to minimize physical property impact, chemical properties began to dominate the lean stability limit. At 3.5% ΔP/P, A-2, C-1, and C-7 all demonstrate the beginning of a transition from physical property to chemical property dependence due to the collapse of their LBO limits at 3.5% ΔP/P and the increase in LBO limit above 3.5% ΔP/P. However, since C-3 did not attain a lower φ_{LBO} than C-1 at ΔP/P less than 5%, physical properties still had an influence between these two conditions. These trends indicated a transition regime rather than a single point, wherein fuels with very poor atomization characteristics shift the minima (improved LBO) to higher ΔP/P.

Random forest regression analysis was leveraged in similar techniques as those used by Peiffer [17]. Random forest analysis is a machine learning technique that utilizes random sampling and replacement, or bagging, to evaluate how different

variables (e.g., fuel properties) impact a particular result (e.g., fuel performance). Around twenty data points are required for a normal pattern to appear [26]. For this analysis, a minimum of thirty data points were considered at each condition. By using bagging techniques, random forests can evaluate and predict importance values for given properties without bias and with lower error than other statistical techniques with small sample sizes [27,28]. Each parameter in the selected regression was evaluated against φ_{LBO}. Linear regression analyses to correlate LBO performance to fuel properties were attempted, but no correlations could be discerned because of the non-monotonic trends. Since only four fuels and relatively small data sets (between 30–40 data points per condition) were used, a more robust statistical analysis method was required.

Weber number (We), defined in Eq. 3, was selected to evaluate physical property and operating condition effects on the fuel spray. Weber number is a dimensionless spray parameter which considers the disruptive aerodynamic forces (ρv^2) and the fuel binding forces (σ/l). It is the ratio between fluid inertial and surface tension forces. By considering the competition between breakup inhibiting and promoting forces, fuel spray quality can be evaluated [3].

$$We = \frac{\rho\, v^2\, l}{\sigma} \tag{3}$$

For the present study, the fuel velocity (v) was unknown so the pressure drop across the nozzle (ΔP_{noz}) was used, due to ΔP_{noz} scaling with v^2. Since the same fuel nozzle was used for all experiments, the characteristic length (l) was equivalent for all fuels tested, which allowed for approximation of Weber number (We_{apr}) as shown in Eq. 4. Density (ρ) and surface tension (σ) were calculated based on the fuel temperature at each point. Random forest analysis was also performed using all three properties considered in We_{apr}, as well as substituting each property individually for We_{apr}, and it was found that the inclusion of only We_{apr} resulted in higher adjusted R^2 (R_{adj}^2) values.

$$We_{apr} = \frac{\rho(T)\Delta P_{noz}}{\sigma(T)} \tag{4}$$

The Ohnesorge number (Oh) was additionally considered to evaluate physical property effects on LBO performance. As shown in Eq. 5, the Ohnesorge number only considers physical properties and was able to be fully evaluated [3].

$$Oh = \frac{\mu(T)}{[\rho(T)\sigma(T)D]^{0.5}} \tag{5}$$

When $\Delta P/P$ was set at 2%, We_{apr}, as well as viscosity, were shown to be the most influential parameters to φ_{LBO} (Figure 4a). At the low $\Delta P/P$ conditions, atomization was strongly controlled by physical properties such as viscosity and those included in We_{apr}. These physical properties affected fuel atomization, which in turn impacted φ_{LBO}. For the range of $\Delta P/P$, ΔP_{noz} was found to be between 48 and 200 kPa. Lefebvre [3] calls out 100 kPa being the minimum ΔP_{noz} required to produce a cone-shaped spray in pressure-swirl nozzles like the one used in this study. This value was not reached for most fuels with $\Delta P/P$ below 3.5%, because the fuel mass flow was low enough that the spray was most likely tulip or onion-shaped rather than a conical sheet, meaning physical properties strongly influenced the LBO limit Interestingly, DCN was also observed to have measurable impact at 2% $\Delta P/P$. However, it is not near the collective impact that We_{apr} and μ have at low $\Delta P/P$, allowing low $\Delta P/P$ to be considered physical property-dominated.

At higher $\Delta P/P$, fuel chemical property influence is observed (Figure 4a) where DCN is the most important property, followed by molecular weight (MW) and We_{apr}. The improved atomization at higher $\Delta P/P$ caused physical properties to have a lesser impact on fuel performance once the 100kPa ΔP_{noz} atomization threshold was surpassed. With comparable atomization characteristics between the fuels, regardless of physical properties, fuel chemical properties evidently impact the LBO limit.

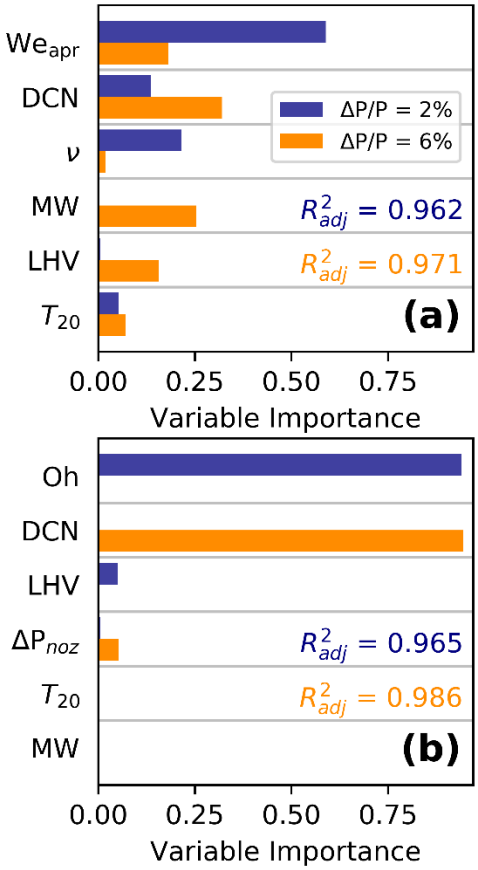

Figure 4. (a) The random forest regression including approximated Weber Number for ΔP/P of 2% and 6%, and (b) random forest results for ΔP/P of 2% and 6% for Ohnesorge number. The Ohnesorge regression results show higher adjusted R2 values than the approximated Weber number.

As shown in Figure 4, the Ohnesorge number clearly illustrates the transition from physical to chemical property dependency with increasing ΔP/P. In Fig. 4b, at 2% ΔP/P, the Ohnesorge number, which considers only physical properties, is observed to be the most important parameter. Because of the low ΔP/P, atomization will be poor, allowing physical properties to dominate LBO performance. In contrast, at 6% ΔP/P, the Ohnesorge has no impact on LBO due to improved atomization, thus, transition to a DCN dominated effect.

Fuel and air temperature was varied at constant ΔP/P=3.5% to examine potential physical-to-chemical transitions via temperature impacts (Figure 5). The fuel performance variance over the temperature range reported here was modest compared to previous studies [27]. Experimental limitations at this configuration required temperatures below 360K. To first order, φ_{LBO} decreased with increasing temperatures, as all break-up and vaporization rates increased at higher temperatures. While most of the fuels were closely grouped, C-3 did not overlap with any of the other fuels, most likely due to its higher viscosity and relatively high distillation temperatures. Together, these properties would account for poorer atomization and vaporization, which led to worse LBO performance for C-3. The φ_{LBO} for C-1 was unaffected by increases in temperature from 34 –355K, which suggests a transition to chemical property transition. Conversely, fuels A-2 and C-7 continued to have a decreased φ_{LBO} at similar conditions. The effect of fuel l and air temperature on the C-3 φ_{LBO} was more pronounced than for the other fuels as evident by its steeper slope.

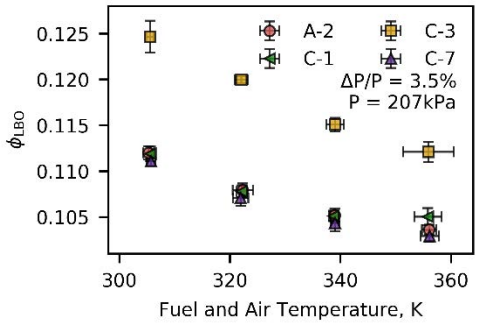

Figure 5. Impact of varying fuel and air temperature on equivalence ratio.

Conclusion

LBO experiments were conducted in a single-cup swirl-stabilized combustor (Referee Combustor) to study the impacts of fuel chemical and physical properties under varying pressure drops across the dome and at varying fuel and air temperatures. The Referee Combustor was designed with turbine engine OEMs input to simulate key characteristics of actual turbine engine combustors. LBO has previously been found to correlate with chemical properties (i.e. DCN) at relatively high air and fuel temperatures and pressures, while at low fuel and air temperatures and pressures LBO correlates most strongly with physical properties such as viscosity.

Results showed that LBO performance (φ_{LBO}) responded non-monotonically to fuel properties and to combustor ΔP/P, and the relative performance of the fuels was found to change with varying ΔP/P. At lower combustor ΔP/P, LBO dependence on physical properties due to poorer fuel atomization was demonstrated. At higher ΔP/P the trends appear to shift to LBO performance being impacted by chemical properties (i.e., DCN). The changeover from physical to chemical property dependence was found to be a range rather than a single temperature or ΔP/P point. Random forest regression analysis using dimensionless parameters demonstrated that an approximate Weber Number and Ohnesorge number were the most influential parameters at low ΔP/P, while DCN was the most impactful property at high ΔP/P.

Milestones

Chemical and physical effects on LBO at various temperature was determined.

Major Accomplishments

Reported the LBO results at various temperature for various fuels.

Publications

Peer-reviewed journal publications

Colborn JG, Heyne JS, Stouffer SD, Hendershott TH, Corporan E. Chemical and physical effects on lean blowout in a swirl-stabilized single-cup combustor. Proc Combust Inst 2020. doi:10.1016/j.proci.2020.06.119. (Article in press)

Outreach Efforts

None

Awards

None

Student Involvement

Jen Colborn, graduate research assistant, leads this effort.

Plans for Next Period

Finalize the publication in progress and for Jen Colborn to finish her M.S.

References

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