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FUEL FLEXIBILITY IN LM2500 AND LM6000 DRY LOW EMISSION ENGINES

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ABSTRACT

The LM2500 and LM6000 dry-low-emissions (DLE) aeroderivative gas turbine engines have been in commercial service for 15 years and have accumulated nearly 10 million hours of commercial operation. The majority of these engines utilize pipeline quality natural gas predominantly comprised of methane. There is, however, increasing interest in nonstandard fuels that contain varying levels of higher hydrocarbon species and/or inert gases. This paper reports on the demonstrated operability of LM2500 and LM6000 DLE engines with non-standard fuels. In particular, rig tests at engine conditions were performed to demonstrate the robustness of the dual-annular counter-rotating swirlers (DACRS) premixer design, relative to flameholding with fuels containing high ethane, propane, and N_2 concentrations. These experiments, which test the ability of the hardware to shed a flame introduced into the premixing region, have been used to expand the quoting limits for LM2500 and LM6000 gas turbine engines to elevated C2+ levels. In addition, chemical kinetics analysis was performed to understand the effect of temperature, pressure, and fuel compositions on flameholding. Test data for different fuels and operating conditions were successfully correlated with Damkohler number.

NOMENCLATURE

d	Diameter of fuel injection orifice
Da	Damkohler number
DACRS	Dual-annular counter-rotating swirler
DLE	Dry low emissions
DP	Pressure drop across combustor dome
ELBO	Enhanced lean blowout
ISO	International Organization for Standardization
LHV	Lower heating value
LNG	Liquefied natural gas
MWI	Modified Wobbe Index
P	Pressure
P_3	Compressor discharge pressure
PSR	Perfectly stirred reactor
r	Momentum flux ratio of fuel jet to air flow
SG	Specific gravity relative to air
T	Temperature
T_3	Compressor discharge temperature
TC	Thermocouple
$\tau_{residence}$	Residence time
$\tau_{chemical}$	Chemical time
u_{fuel}	Fuel jet velocity
x_i	Regression variable
z	Probability of flameholding
β_i	Regression coefficient
μs	microsecond

INTRODUCTION

The LM2500 and LM6000 dry-low-emissions aero-derivative engines were designed to operate with standard gaseous fuels having modified Wobbe Indices between 40-60. The MWI of a fuel is a measurement of energy content per unit volume and is defined as:

$$MWI = LHV / (SG_{gas} * T_{gas})^{0.5} \quad (1)$$

where LHV is in BTU/scf, and T_{gas} is the fuel temperature in Rankine. Due in part to high fuel costs, development of LNG production facilities, and limits on the flaring of process gases, there is increasing interest in burning nonstandard fuels with elevated levels of inert (N_2, CO_2, etc.) and/or C2+ constituents such as C_2H_6, C_3H_8, and C_4H_{10}. The consideration of nonstandard fuels for use in lean premixed combustion systems includes the impact that fuel composition can have on fuel system sizing, dew point and superheat requirements, compressor stall margin, flammability limits, flameholding, autoignition, emissions, and combustion stability. GE's DLE field experience indicates that acceptable emissions and operability are achievable at MWI levels as low as 37 and with fuels having 15% C2+ by volume. Recent factory engine testing has indicated the potential to extend the lower MWI limit below 35 [1]. This paper discusses component rig testing used to validate increases in allowable C2+ levels.

The LM2500 and LM6000 DLE engines use tri-annular combustors with common premixer technology based on dual-annular, counter-rotating swirlers. Base load compressor discharge pressure and temperature at ISO conditions range from 275-460 psia (18.7-31.3 atm) and 860-1000°F (733-811 K). Engine bleed and fuel staging allow lean premixed operation throughout the operating range. In each staging mode, emissions and acoustics can be optimized by varying the flame temperatures within each dome partition, typically between 2700-3200°F (1755-2033 K) [2].

The design and development of DACRS premixer technology have been previously discussed by Joshi et al. [3]. A cross-section of a dual-fuel DACRS premixer is shown in Fig. 1 [4]. Design features include outer and inner axial swirlers that counter rotate to prevent vortex breakdown inside the premixing duct. A converging mixing duct continuously accelerates the fuel-air mixture to limit boundary layer growth and maintain flow velocities in excess of turbulent flame speeds. The conical centerbody used for liquid fuel injection in dual-fuel design is purged with air to prevent flameholding at the tip. Gaseous fuel injection orifices are located near the outer vane trailing edges (premix), in the outer flow path surface between vanes (premix), and at the trailing edge of the premixer shroud (ELBO). Residence times inside the premixing duct are on the order of 1 millisecond. The turbulent shear layer developed at the interface of the counter-rotating swirler vanes enhances mixing, resulting in a nearly uniform fuel-air profile at the premixer exit plane. DACRS designs have been successfully scaled to accommodate different airflow requirements for variants of the LM2500 and LM6000 DLE combustion systems.

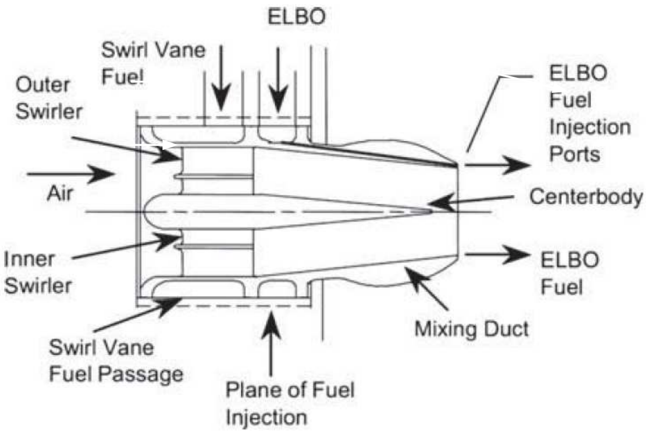


Figure 1 Cross section of DACRS premixer.

In premixed combustion systems, ignition of the fuel-air mixture inside the premixer can occur via auto-ignition, flashback, or ingestion of hot combustion gases caused by combustion dynamics or other transient events such as compressor stall. A robust premixer design prevents flameholding by rapidly sweeping high-temperature combustion product out of the mixing duct into the combustor before hardware damage occurs. Fuel composition influences auto-ignition, flashback, and flameholding by changing chemical kinetic time scales, the speciation of intermediate reactants and radicals, and the relative rates of mass and thermal diffusion [5]. In addition, changes in fuel jet momentum ratio relative to the surrounding air stream modify jet penetration and fuel-air mixing [6]. Flashback is thought to occur most frequently in boundary layers where flow velocities are lowest; however, vortex breakdown in highly swirling flow fields can also result in flame propagation into the mixing duct if axial velocities drop below the turbulent flame speed. Design robustness can be demonstrated in component tests at the most severe operating conditions expected, including cycle conditions (P_3, T_3, and dome DP), fuel-air ratios, fuel compositions, and manufacturing variation.

TEST SETUP AND PROCEDURE

Flameholding tests were conducted in a high-pressure combustion rig, as shown in Fig. 2, designed to operate with two DACRS premixers. The rig is rated for 867K and 41 atm and thus can cover all the aeroderivative engine conditions. A backpressure valve is used to adjust the airflow velocity through the premixers by controlling the pressure drop across the dome.

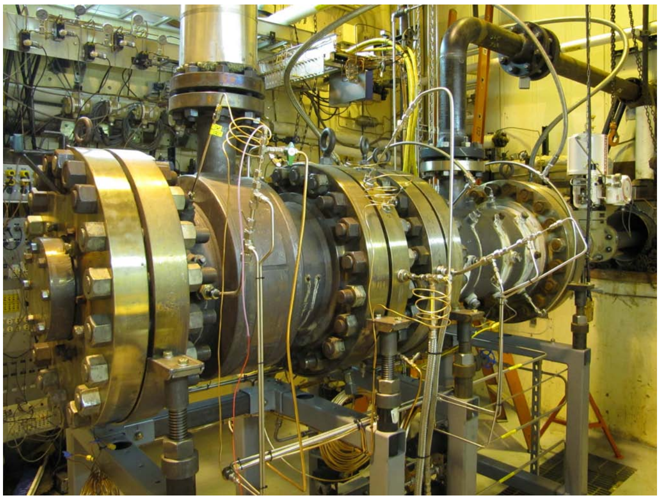


Figure 2 High-pressure, 2-cup combustion test rig.

Figure 3 shows the test section for the 2-cup combustion rig. Two identical premixers were used for flameholding test in this work. A H_2 torch was mounted upstream of each premixer to ignite the fuel/air mixture to initiate combustion. Due to plenum feed, the air flow is uniformly distributed between two premixers. Each premixer was instrumented with thermocouples to monitor metal temperatures in the premixing duct. Pressure transducers were used for static pressures (P_3, P_4), dome pressure drop, and dynamics pressure monitoring. An emissions sampling probe was mounted downstream of each cup centerline to measure CO and NOx emissions and assess fuel-air ratio closure. The combustion products were cooled by water spray before flowing into exhaust duct.

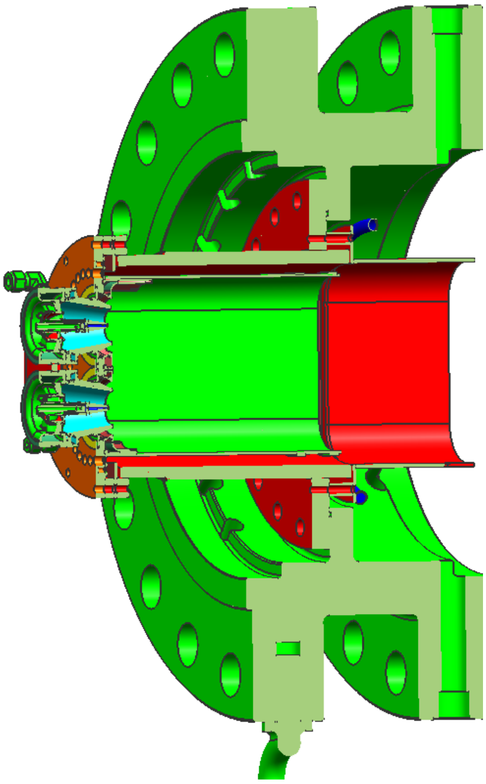


Figure 3 Cross section of the high pressure 2-cup combustion test rig.

The tests reported in this paper are the continuation of the fuel flexibility work described in Ref. 1. Liquid propane was pumped into an electric vaporizer and heated beyond the critical temperature. Ethane and nitrogen were supplied via gas cylinders. Propane, ethane, or nitrogen are mixed with natural gas in a manifold upstream of the test rig. As shown in Fig.4, each premixer has two independent fuel lines, one for premix fuel injection and one for ELBO fuel injection. The ELBO fuel was maintained at a fixed percentage of the total fuel for each premixer during flameholding testing.

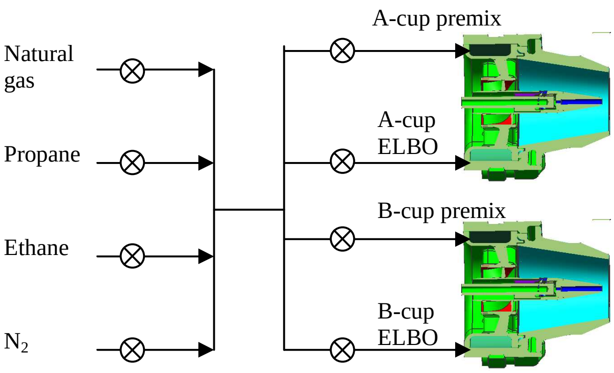


Figure 4 Schematic of fuel supply to the two DLE premixers in combustion rig.

The effect of C2+ content on flameholding was examined by adding ethane or propane to natural gas during fired operation. After steady operation is achieved, the H_2 torch was briefly fired upstream of one premixer. The temperature rise of thermocouples embedded in the premixer shroud and centerbody were monitored to assess whether they would return to T_3 levels (i.e., no flameholding) or continue to rise (indicating flameholding). To protect the hardware, these thermocouples were interlocked to shut off the fuel flow when a threshold temperature was exceeded. Multiple torch tests were conducted at each operating condition to account for system and/or event variability. Figure 5 shows the example of the transient thermocouple response during multiple firings of the upstream torch at conditions where flameholding did not occur. Figure 6 shows an example of the response when flameholding occurred, followed by fuel flow termination by the TC interlock.

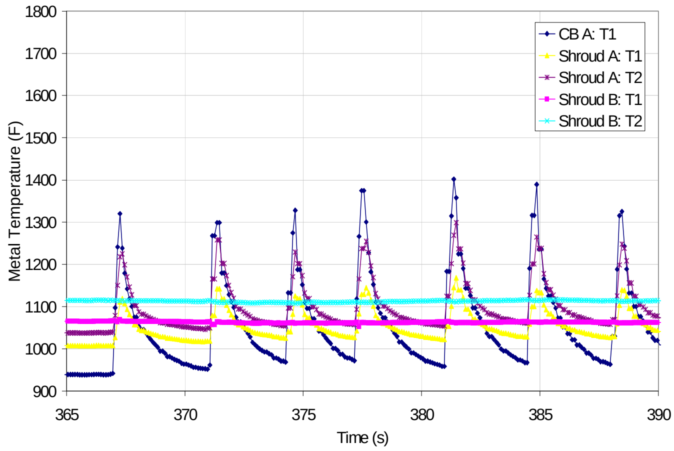


Figure 5 Transient response of premixer TC's at conditions where flameholding did not occur.

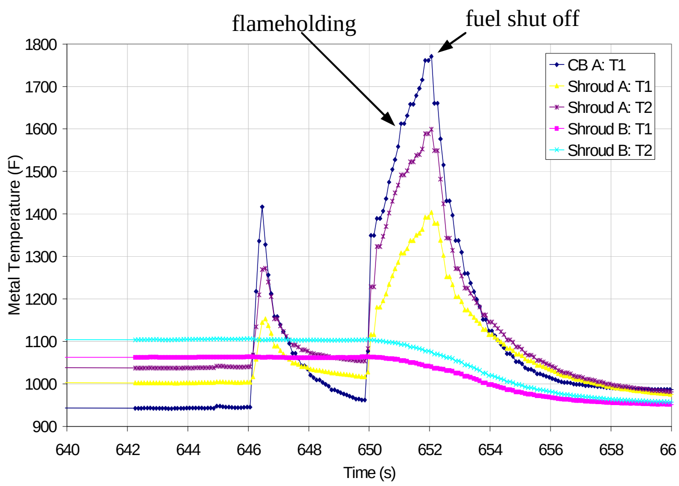


Figure 6 Transient response of premixer TC's when flameholding occurred on second pulse of H_2 torch.

Tests were conducted at pressures between 300 to 480 psia (20-33 atm), preheat air temperatures of 800 to 1010 ^oF (700-816 K), flame temperatures of 3000-3400 ^oF (1922-2144 K), and dome pressure drops of 2.5 to 4%. Data were analyzed using a second order binary logistic regression due to the discrete nature of the data (hold/no-hold), where the probability of an event happening is fit to a logistic function, which has a linear dependence on the predictor variables:

$$z = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n \quad (2)$$

The goal of the regression is to determine the coefficients β_i of the variables x_i. All of the flamholding test data were run through a single binary logistic regression that included second order and cross terms for the following variables: Dome DP/P, P_3, T_3, flame temperature, and C_2 or C_3 percent. The regression results were used to identify terms that were not significant (if p score > 0.05). The terms with the highest p score were eliminated from consideration until all remaining terms had p score < 0.05.

The flameholding threshold was determined in two ways: (1) from the experiments as the lowest ethane or propane concentration where flameholding was observed; (2) from the analysis as the ethane or propane concentration where there was a 90% probability of not flameholding. In general, the flameholding thresholds identified by these two methods agree with each other.

RESULTS AND DISCUSSION

Multiple tests were conducted at each fuel composition and cycle condition to determine flameholding probability. In the following figures, test points where flameholding was observed are shown as solid symbols (fail), and test points where flameholding did not occur are shown as open symbols (pass). The 90% no-flameholding probability line from the binary logistic regression is also shown in the figures. Flameholding was not observed for N_2 doping in natural gas; thus no N_2 doping test data are shown in this section.

Figure 7 shows the effect of pressure on the flameholding boundary for propane mixed with natural gas. For fixed pressure and preheat temperature, the propane concentration was increased while the flame temperature was kept constant at ~3200 ^oF. At low propane levels, there is no flameholding in the premixer. As the propane content increases, the probability of flameholding increases due to higher reactivity and fuel density of propane compared to methane (and thus lower fuel jet velocity). At each P/T combination, a threshold C3 level was reached above which the probability of flameholding increased. As see in Fig.7, this threshold level decreased from ~50% (by volume) C_3H_8 at 300 psia to ~30% (by volume) C_3H_8 at 480 psia.

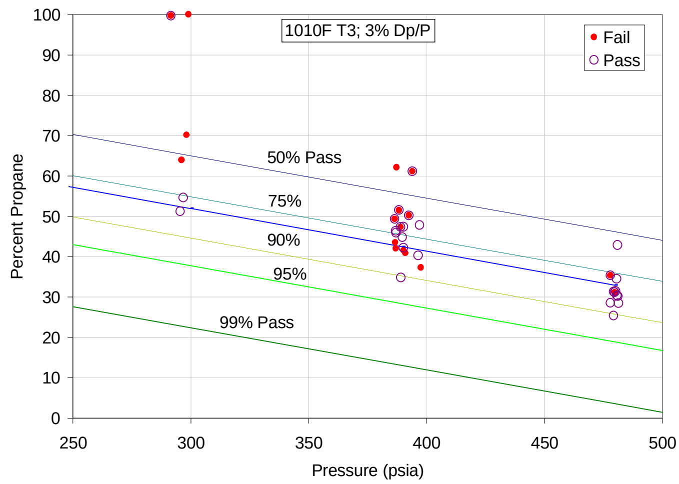


Figure 7 Flameholding test results with propane mixed with natural gas.

The effect of flame temperature on flameholding limit is shown in Fig. 8. When flame temperature varied from 3000 ^OF to 3400 ^OF, the change in the flameholding threshold was not significant. This observation is corroborated by binary logistic regression analysis, which showed flame temperature to be an insignificant parameter. As a result, no regression line is shown in Fig. 8.

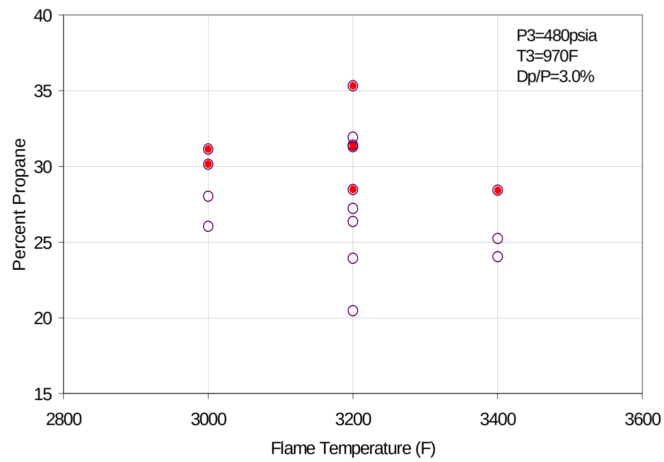


Figure 8 Effect of flame temperature on flameholding. Propane mixed with natural gas.

Figure 9 shows the effect of compressor discharge temperature on flameholding. The lowest flameholding propane concentration decreased from approximately 65% C_3H_8 at T_3=800 ^OF to nearly 40% C_3H_8 at T_3=1010 ^OF. As indicated by the binary regression curve, this reduction is non-linear in T_3.

The data in Fig. 7 and 9 suggest that mixture flame speed is not the governing parameter for flameholding. For hydrocarbon fuels, flame speeds depend more heavily on flame temperature than on T_3, and decreases with increasing pressure. The observations that the flameholding probability is more strongly dependent on T_3 than on flame temperature, and increases with P3 are counter to expectations based on flame speed considerations alone.

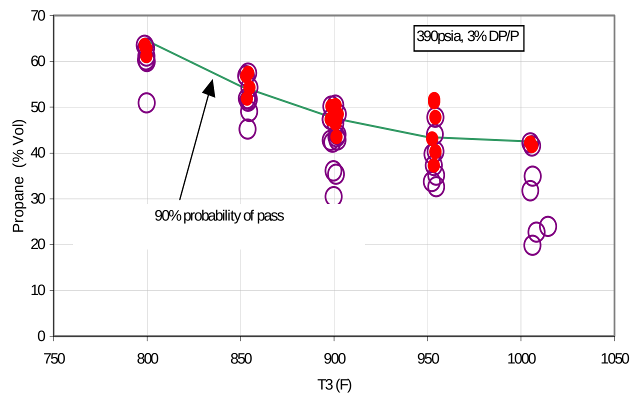


Figure 9 Effect of T3 on flameholding. Propane mixed with natural gas. (Flame temperature was kept constant.)

The impact of combustor dome DP/P on flameholding is shown in Fig. 10. The dome pressure drop DP/P determines the velocity of the fuel-air mixture in the premixer. As indicated by the data, higher mixture velocities increased resistance to flameholding. The experimental data indicate a monotonic increase for the flameholding threshold between DP/P=2.5% to DP/P=4%. The binary logistic regression results indicated a quadratic dependence with a change in slope around DP/P=3.5%. Over the conditions studied, the experiments and the regression results agree within 5%.

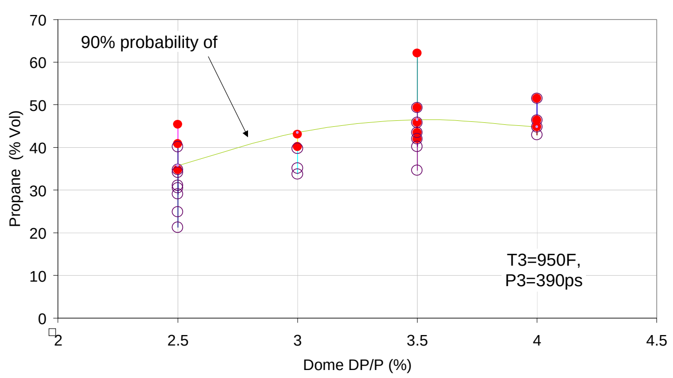


Figure 10 Effect of DP/P on flameholding. Propane mixed with natural gas. (Flame temperature was kept constant.)

The flameholding tendencies of ethane and propane can be compared using experimental data. The previous work focused on the effect of pressure [1], so the comparison in Fig.11 is plotted with fuel concentration as a function of pressure. This figure plots all flameholding data for both fuels at T_3=1010 ^oF and DP/P=3%. Overall, no significant difference is seen between the two sets of data. Propane has a slightly higher flameholding concentration at 300 psia and 375 psia, while ethane has a slightly higher flameholding concentration at 480 psia.

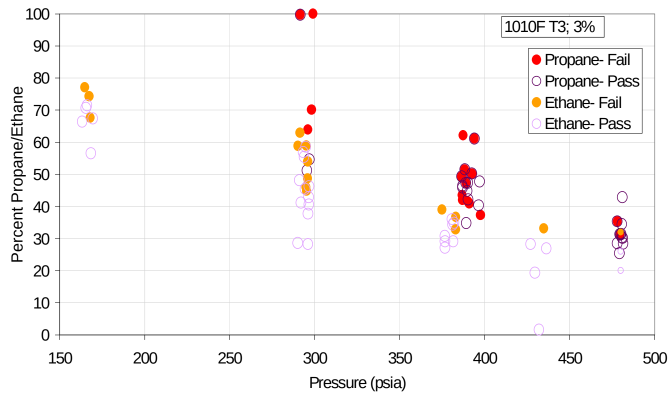


Figure 11 Comparison between ethane and propane flameholding tendency when mixed with natural gas.

CHEMICAL KINETICS ANALYSIS

Chemical kinetic analyses were performed to understand data trends and the dependence of flameholding on preheat temperature, pressure, and DP.

Figure 12 illustrates a perfectly stirred reactor (PSR) used to model the flameholding phenomena in the DACRS premixer for the mixture of premix fuel and air. ELBO fuel is injected outside of the premix duct, and thus is not important for flameholding phenomena. The simulations were performed with GRI-Mech 3.0 [7]. Air properties (such as T_3, P_3, mass flow rate) are known from test conditions. Fuel supply temperature is estimated to be 500K at injection location due to tube heating inside the pressure vessel.

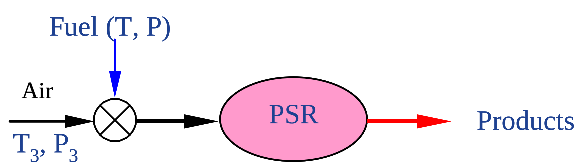


Figure 12. Schematic of the perfectly stirred reactor used to model flameholding in DLE premixers.

Methods for developing blowout and flashback correlations using PSR models have been studied extensively [8, 9]. However, they lead to essentially the same form of correlation [10], relating blowoff or flashback limits to a Damkohler number defined as

$$Da = \frac{\tau_{residence}}{\tau_{chemical}} = \frac{\sqrt{rd} / u_{fuel}}{\tau_{chemical}} \quad (3)$$

In this work, the characteristic residence time is derived from considerations of flameholding inside wakes caused by fuel jets in cross-flow with the incoming air. It is assumed that the fuel jet wake is proportional to the jet penetration length, and scales with $\sqrt{rd} / u_{fuel}$. This scaling parameter explicitly includes the effect of fuel/air momentum ratio.

In this work, the chemical time is estimated using a blowoff time, which has been shown as the characteristic time for different flameholding/flashback mechanisms including boundary layer propagation, and combustion induced vortex breakdown. Figure 13 shows the generalized approach to determine blowoff time with PSR. As the residence time of PSR is reduced, the product temperature decreases, slowly at first, until a threshold blowoff time is reached at which the temperature abruptly drops to the initial temperature. Therefore, blowoff time is the minimum PSR residence time required for the fuel air mixture to have reaction or heat release. To simplify the analysis, the blowoff time is calculated for a stoichiometric mixture assuming flameholding occurs in a stoichiometric surface near fuel injection.

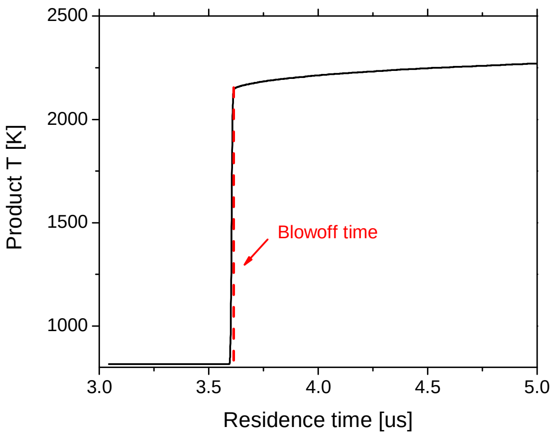


Figure 13. Product temperature as a function of PSR residence time, showing the definition of blowoff time.

Figure 14 shows the blowoff time as a function of percent propane in fuel mixture. As the amount of propane increases, the blowoff time decreases, indicating the fuel/air mixture is reactive and therefore more prone to flameholding. This trend is in agreement with the test data shown in Fig.14. Furthermore, PSR modeling indicates that air inlet temperature (T_3) and pressure (P_3) have significant effect on blowoff time, as shown in Fig.15. These trends are consistent with test results, demonstrating the use of blowoff time as a means to explain the flameholding dependences. As seen in Fig. 14 and 15, the data indicate a more abrupt transition in flameholding probability than that indicated by PSR blowoff times. This may suggest that a more detailed model is needed to fully capture flameholding phenomena.

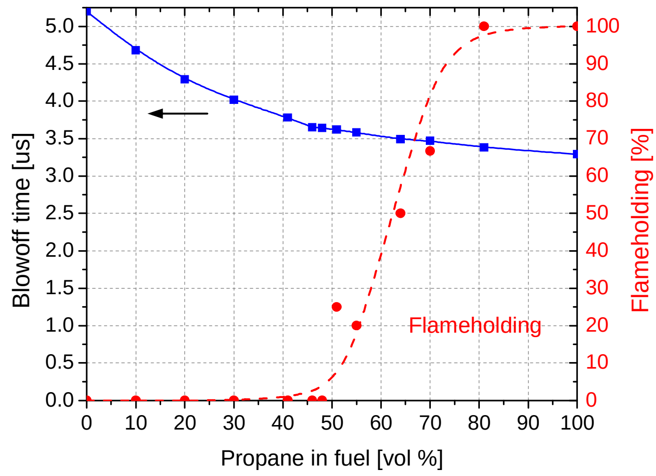
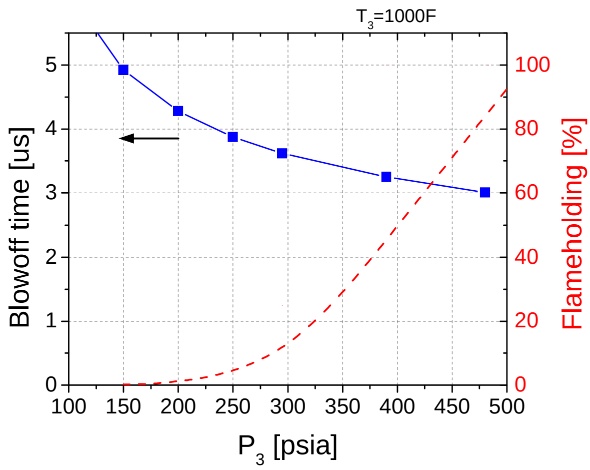


Figure 14. Comparison of calculated blowoff time with flameholding probability. Dot: test data; dash line: binary regression. 300psia, 1000°F, dP/P=3%, Tflame=3200°F.



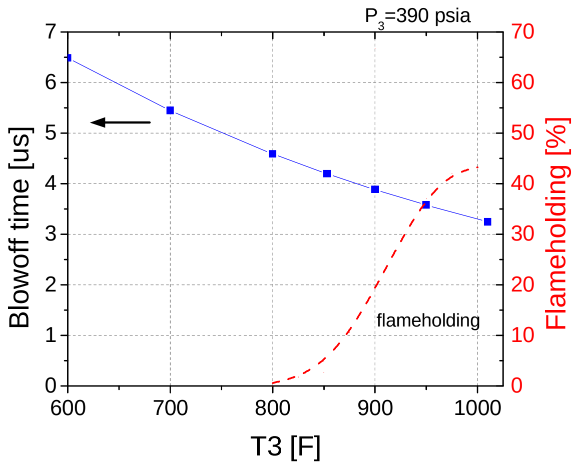


Figure 15. Effect of P_3 and T_3 on blowoff time and flameholding probability. 51% C_3H_8 (by vol) in natural gas.

Ethane and propane are more reactive than methane due to different oxidization pathways. For example, higher-order alkyl radicals and great variety of minor species with greater instability, can form during ethane or propane oxidization [10]. Figure 16 plots the comparison of calculated blowoff time when natural gas is doped with ethane or propane. Inlet air flow conditions and flame temperature are kept the same in the calculation. Both ethane and propane doped fuels show similar trends and little difference in blowoff time at a given percentage of C2+.These results are in agreement with the data in Fig.11.

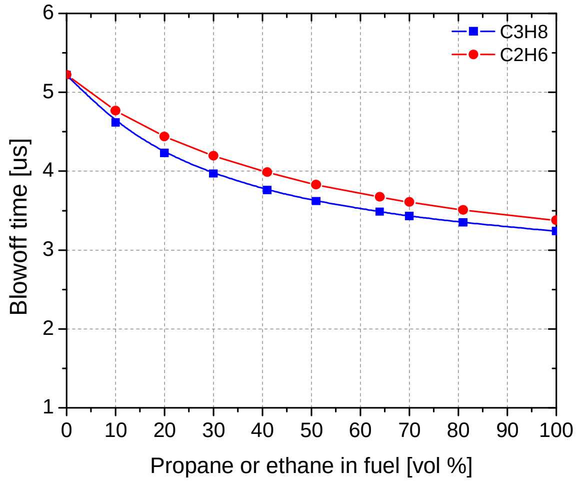


Figure 16. Calculated blowoff time as a function of propane or ethane in fuel. 295psia, 1010^{o}F.

The flameholding test data with different fuels and at different test conditions can be collapsed with the Damkohler number correlation. Figure 17 plots all the flameholding test data. The characteristic parameter in the y-axis is derived from Eq.(3) and represents a characteristic jet velocity for flameholding to occur when it is larger than the fuel jet velocity. The slope of the line through the data is the characteristic Damkohler number. There is some scatter to the data, likely due to both experiment and modeling uncertainties. However, most of the flameholding data points (both ethane and propane in natural gas) are above the line, while most of the non-flameholding data are below the line.

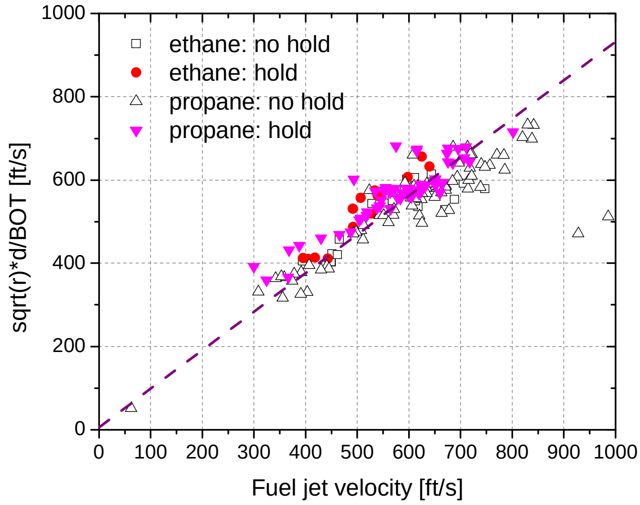


Figure 17. LM6000 flameholding test data for different test conditions.

Figure 18 plots the Damkohler number at the flameholding threshold, i.e., where flameholding starts to occur when the ethane or propane concentration is increased while keeping all other conditions fixed. The Damkohler number is nearly constant at the flameholding threshold for different test conditions (C_2H_6 or C_3H_8, T_3=730-1010^{o}F , P_3=150-480psia, dP/P=2-4%). The test point with 27% N_2 and 73% C_3H_8 yields slightly larger Da, perhaps due to uncertainty in the GRI reaction mechanism for C_3H_8 oxidation. However, all other test data (C_2H_6 or C_3H_8 from 25% to 100%) are close to the line with Da=1.

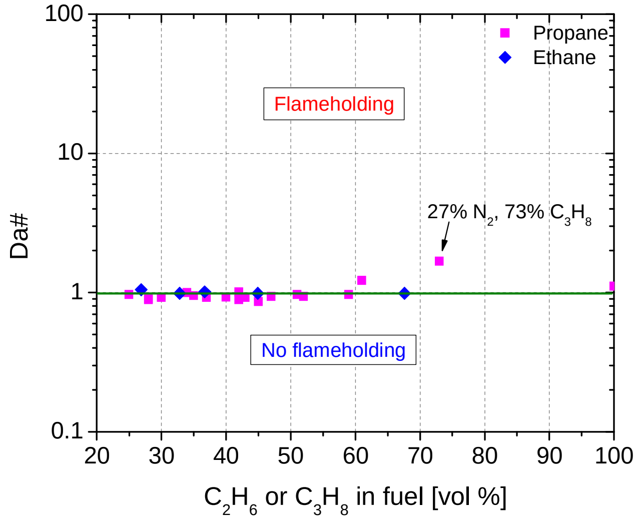


Figure 18. Damkohler number at flameholding boundary for different test conditions.

CONCLUSIONS

There is increasing interest in operating LM2500 and LM6000 DLE engines with nonstandard fuels that contain increasing levels of higher hydrocarbon species and/or inert gases. This paper reports on the rig tests at engine conditions to demonstrate the robustness of the dual-annular counter-rotating swirlers (DACRS) premixer design, relative to flameholding with fuels containing high ethane, propane, and N_2. Test results show sensitivity of flameholding to preheat air temperature and pressure, mild sensitivity to dome pressure drop DP, and minor sensitivity to flame temperature. For high pressure ratio cycles typical of aeroderivative gas turbines, no significant difference is seen for flameholding boundary between ethane addition and propane addition to natural gas.

Chemical kinetics analysis was performed to understand the effect of temperature, pressure, and fuel compositions. Calculated PSR blowoff times correlate well with the observed data trends. Flameholding test data for different fuels and operating conditions were successfully correlated with a constant Damkohler number.

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