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ALTERNATE-FUELED COMBUSTOR-SECTOR PERFORMANCE

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Abstract

In order to realize alternative fueling for military and commercial use, the industry has set forth guidelines that must be met by each fuel. These aviation fueling requirements are outlined in MIL-DTL-83133F(2008) or ASTM D 7566 Annex (2011) standards, and are classified as “drop-in” fuel replacements. This paper provides combustor performance data for synthetic-paraffinic-kerosene- (SPK-) type (Fisher-Tropsch (FT)) fuel and blends with JP-8+100, relative to JP-8+100 as baseline fueling. Data were taken at various nominal inlet conditions: 75 psia (0.52 MPa) at 500 °F (533 K), 125 psia (0.86 MPa) at 625 °F (603 K), 175 psia (1.21 MPa) at 725 °F (658 K), and 225 psia (1.55 MPa) at 790 °F (694 K). Combustor performance analysis assessments were made for the change in flame temperatures, combustor efficiency, wall temperatures, and exhaust plane temperatures at 3%, 4%, and 5% combustor pressure drop (%ΔP) for fuel: air ratios (F/A) ranging from 0.010 to 0.025. Significant general trends show lower liner temperatures and higher flame and combustor outlet temperatures with increases in FT fueling relative to JP-8+100 fueling. The latter affects both turbine efficiency and blade/vane life.

Keywords: gas turbine engines, combustors, SPK-FT fuel, alternate fuel, combustor performance

Introduction

Finding an alternative fuel for aviation application requires a fuel feedstock with sustainable supply at a low cost with low or no negative environmental impact. The requirements for these “drop-in” fuel replacements are outlined in the MIL-DTL-83133F(2008) or ASTM D 7566 Annex (2011), approved standards for military and civil use, respectively. Alternate jet fuels need to be compatible with current engines and aircraft fuel handling systems in order to reduce the need for new systems to accommodate new fuels that may perform differently than the currently used petroleum fuels.

Even proven alternate fuels face tough issues such as secure, sustainable productivity at competitive pricing. Recently, the Federal Aviation Administration (FAA) announced support of eight companies conducting research into commercial jet fuel alternatives that conform to ASTM D 7566 and are based on resources readily available in the United States [1]. One of the ideas being explored is to produce aviation fuels from carbon monoxide given off by industrial waste gases that would otherwise add to atmospheric pollution. Another idea is to explore the conversion from cellulosic and conventional plant sugars to fuels. Others involve the development of catalysts to convert different carbon sources into fuels in small-scale reactors to serve as distributed fuel production sources. Currently, the biofuels used by the US Navy cost about $26/gal ($6.87/L) [2]. The money that the FAA is funneling into these project could boost the production of cost-effective fuels from biomass and waste feedstocks to afford a potential for commercial and military aviation fueling. Yet to date, the alternate fuels industry competitive costs and productivity have not responded to feedstock restraints, incentives, subsides, or mandates, and compliance taxes are passed to consumers [3].

Adopting alternate fuels and fuel blends requires the use of fuel-flexible systems (combustors and engines) without sacrificing performance requirements. For military aviation, an alternative for traditional fuel for gas turbine and diesel systems is required. However, in many proposed alternates, the lack of sufficient amounts of aromatics that swell some fuel system seals and sulfur, which provides fuel injection pump lubricity, has the potential to reduce design component useful life [4]. For these fuels, additives are needed to increase useful component life while maintaining the performance. It is thought that FT-type fuels can support gas turbine engines at similar levels as well as have potential use for diesel systems.

This paper provides preliminary combustor performance data for SPK-type FT fuel and blends relative to pure JP-8+100 (herein referred to as "JP-8"), the currently used aviation fuel. Data for "Combustor A," a three-cup sector representative of current engine combustor technology (see CFD images [6], proprietary details withheld), were taken at 0%, 50%, and 100% FT fueling (denoted as JP-8, 50:50, and FT, respectively) with varied parameters of fuel:air ratio (*F/A*), percent combustor pressure drop (%ΔP), and absolute pressure. The data collected show that higher combustor operating temperatures have the potential to enhance system efficiency, but also take a toll on component life, as they have a greater impact on the oxidation and failure of the materials within the combustor and turbine. A small temperature difference of combustor gas entering the turbine can both be critical to turbine life and affect efficiency; there is a need for a good balance. "Bleed air," used to cool the combustor, case, turbine blades, vanes, and nozzles, could be increased to compensate for the enhanced turbine inlet temperature; this parasitic air decreases the system efficiency but helps to maintain a reasonable turbine life.

Fuel specifications; the test facility conditions, operations, schematic, and fueling system; estimates of measurement errors; and combustor thermal data and postprocessing parameters of Combustor A are given in the Shouse, et al. paper presented at ISROMAC 13 [5]; the computational fluid dynamics (CFD) analysis and figures of combustor geometry and flow are in the Ryder, et al. paper [6] also presented there. Compositional examination of the synthetic-paraffinic kerosene with the compositional-explicit distillation curve method is discussed in Bruno et al. [7] who makes a useful comparison for heats of combustion based on molecular weight, volume, and mass.

Combustor Thermal Performance

The proprietary-geometry combustor, labeled as "Combustor A," used for data collection represents a three-cup sector of a current engine combustor technology. The Shouse, et al. paper [5] outlines the results given for the 225-psia (1.55-MPa) inlet condition, for three fueling compositions and three *F/A* at 3% ΔP, and this paper continues to analyze all four inlet combustor conditions at all three combustor ΔP values tested for the Fischer-Tropsch fuel blends of 0%, 50%, and 100% with JP-8 fueling. Data were taken at various nominal inlet conditions as follows:

1. FT fuel composition: 0%, 50%, and 100% (±5%)
2. Pressure (*P*) and temperature (*T*): 75 psia (0.52 MPa) and 500 °F (533 K), 125 psia (0.86 MPa) and 625 °F (603 K), 175 psia (1.21 MPa) and 725 °F (658 K), and 225 psia (1.55 MPa) and 790 °F (694 K).
3. Combustor pressure drop ΔP: 3%, 4%, and 5%
4. Fuel:air ratios (*F/A*): 0.010, 0.015, 0.020, and 0.025

Combustor performance analysis assessments were made for the change in flame temperatures (T_{flame}), combustor efficiency, wall temperatures, and exhaust plane temperatures (T_{plane}).

The combustion efficiencies do not provide enough insight for determining significant combustor changes, yet they do show a trend to decrease with increased %ΔP; thus, other aforementioned (T_{flame} and T_{plane}) parameters will also be investigated.

Table 1 Combustor efficiency data summary
[$(P,T)_{inlet}$ = [75 psia (0.52 MPa), 500 °F (533 K)].]

%Δ*P*	3%		4%		5%	
F/*A*	0.010–0.020	0.025	0.010–0.020	0.025	0.010–0.020	0.025
Fuel	Efficiency, %					
JP-8	99.61	99.32	99.56	99.10	99.46	99.20
50:50	99.65	99.24	99.56	99.09	99.46	98.90
FT	99.66	99.20	99.58	98.96	99.48	98.87
Average	99.64	99.25	99.56	99.05	99.47	98.99
St. Dev.	0.024	0.058	0.011	0.080	0.013	0.181

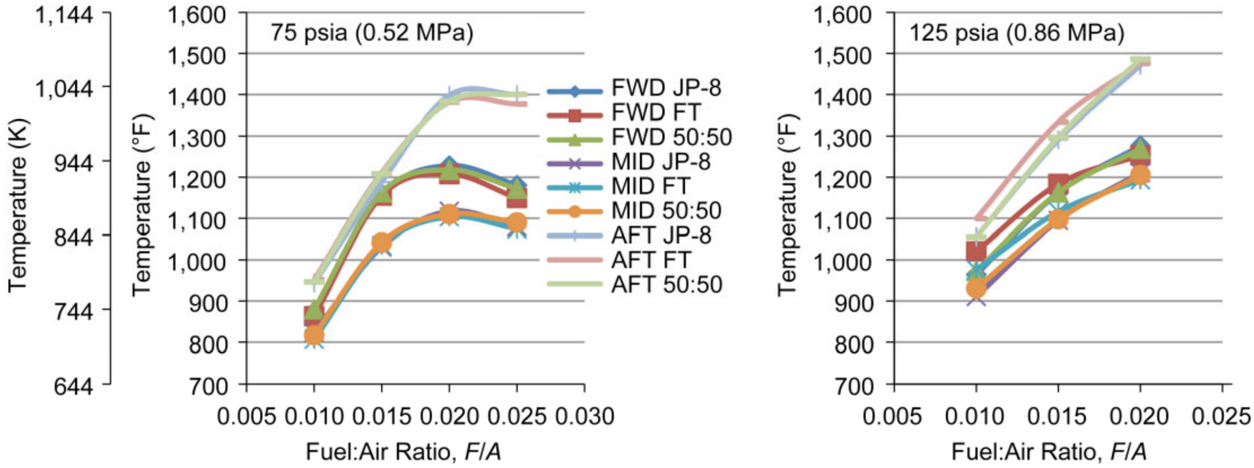

Fig.1 Sidewall temperature variation along the combustor (from FWD to AFT) with *F*/*A* and fuel composition at 4% Δ*P* for $(P,T)_{inlet}$ = [75 psia (0.52 MPa), 500 °F (533 K)], and $(P,T)_{inlet}$ = [125 psia (0.86 MPa), 625 °F (603 K)].

At 75 psia (0.52 MPa) the combustion efficiency of all fuel blends are outlined in Table 1 [5].

Surface Thermal Measurements

Thermocouples and pressure taps were placed throughout the combustion chamber to record temperature and pressure. The details of pressure drop measurements will not be presented in this paper, but it should be noted that no inconsistent pressure measurements were found. The convection-cooled liner and wall surface temperature measurements are noted as sidewall or liner (i.e., facing inside or outside of the liner).

Sidewalls

The forward, middle, and aft axial positions of the thermocouples along the sector combustor sidewalls are represented as FWD, MID, and AFT. Figure 1 represents the sidewall temperature data obtained from the $(P,T)_{inlet}$ = [75 psia (0.52 MPa), 500 °F (533 K)], and $(P,T)_{inlet}$ = [125 psia (0.86 MPa, 625 °F (603 K)], runs at 4% Δ*P*. This figure adequately represents the sidewall temperature trends shown for all inlet pressures and %Δ*P*. Sidewall temperature profiles illustrate a decrease in temperature from the FWD to MID sections and an increase in temperatures from the MID to AFT along the combustor, where the temperatures are highest. The temperatures also increase as the *F*/*A* increases, the only exception being the *F*/*A* of 0.025 at 75 psia (0.52 MPa) inlet pressure, which slightly decreases in temperature relative to the *F*/*A* of 0.020. The 75 psia (0.52 MPa) data set is the only one that includes *F*/*A* of 0.025. Data for 75 psia (0.52 MPa) at 3%, 4%, and 5% Δ*P* at the *F*/*A* of 0.025 are consistent with this trend, with insufficient data to conclude whether this is a peak in combustor temperatures around *F*/*A* = 0.020. The sidewall temperatures depend strongly on *F*/*A* and weakly on the fuel blend composition.

Unwrapped Combustor Liner

Figure 2 is a representative plot of the unwrapped liner surface temperatures; this for *F*/*A* of 0.010 at $(P,T)_{inlet}$ [75 psia (0.52 MPa), 500 °F (533 K)], The term "unwrapped" refers to the normalized outside liner surface circumference (0 to 1) along with the normalized inner liner circumferential surface (1 to 2) as a continuous loop mapped onto a plane. The unwrapped combustor liner temperature profile shows a peak temperature increase measured by the thermocouple as %ΔP increases as well as an increase with *F/A*.

The absolute inlet pressure and temperature of the system also shows an effect on the peak liner temperature (Fig. 2). Overall, the peaks in the temperature profile become more pronounced as *F/A* increases. They also become more pronounced as %ΔP increases, but *F/A* appears to have the greater effect.

Using Fig. 2, it is difficult to differentiate between the temperature differences of the varied fuel blends. By calculating the difference in temperatures read by the thermocouples at each location on the combustor for the blend and the 100% FT fuel relative to those recorded for JP-8 ,that is, $\Delta T = T_{\text{fuel blend}} - T_{\text{JP-8}}$, a better sense for each fuel's performance may be obtained. Figure 3 illustrates the trends seen for the average temperature differences in relation to *F/A* at $(P,T)_{\text{inlet}}$ = [125 psia (0.86 MPa), 625 °F (603 K)] and [225 psia (1.55 MPa) and 790 °F (694 K)] at

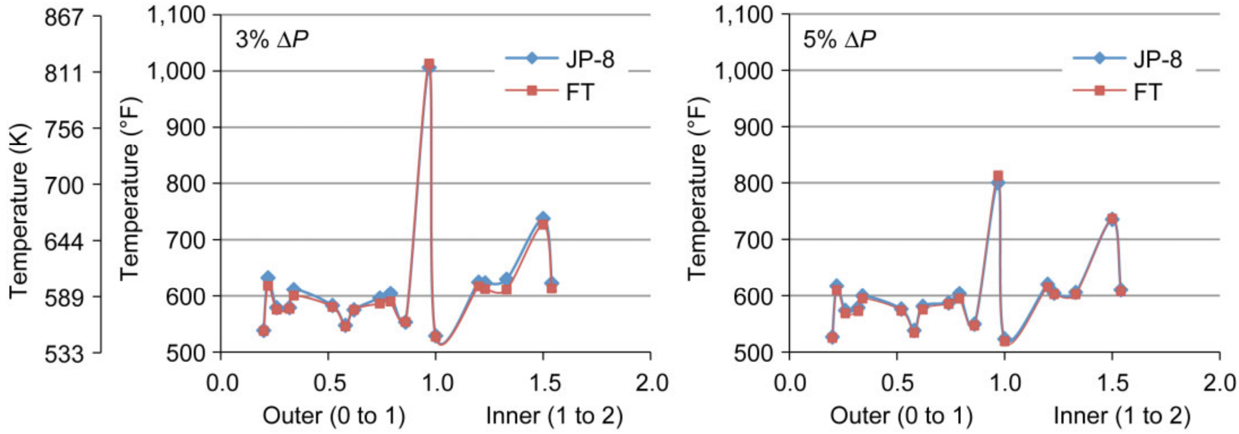

Fig.2 Unwrapped liner temperature profile for *F/A* = 0.010 and $(P,T)_{\text{inlet}}$ = [75 psia (0.52 MPa), 500 °F (533 K)] at 3% and 5% ΔP.

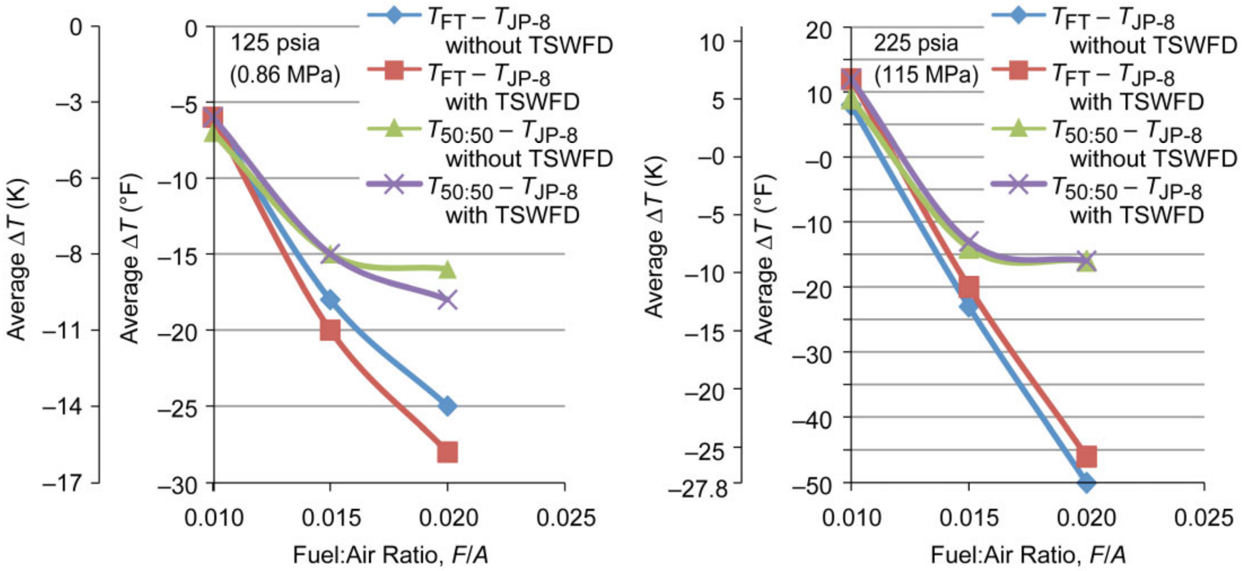

Fig.3 Average liner temperature differences ($\Delta T = T_{\text{fuel blend}} - T_{\text{JP-8}}$) versus *F/A* for $(P,T)_{\text{inlet}}$ = [125 psia (0.86 MPa), 625 °F (603 K)] and [225 psia (1.55 MPa), 790 °F (694 K)] at 3% ΔP. The sidewall temperature at the FWD position (TSWFD) was found to be a possible outlier and was excluded from one set of averages for a better comparison. Temperatures represent combined heat transfer effects.

Table 2 Average Unwrapped Liner Temperature Differences:[a,b] FT Fuel and 50:50 Blend With Respect to JP-8+100 ($T_{\text{fuel blend}} - T_{\text{JP-8}}$) (°F) [$\Delta T$ (°F) = 1.8ΔT (K)

		F/A = 0.010			F/A = 0.015			F/A = 0.020			F/A = 0.025		
Inlet Pressure	%ΔP	JP-8	FT	50:50	JP-8	FT	50:50	JP-8	FT	50:50	JP-8	FT	50:50
75 psia (0.52 MPa)	3%	0	–4	–5	0	1	–6	0	–15	–11	0	–12	–16
	4%	0	–2	0	0	–2	–2	0	–9	–7	0	–12	–8
	5%	0	–3	–2	0	–1	–2	0	–2	–3	0	–3	1
125 psia (0.86 MPa)	3%	0	–6	–6	0	–20	–15	0	–28	–18			
	4%	0	1	–1	0	–6	–6	0	–29	–16			
	5%	0	6	2	0	–10	–5	0	–23	–11			
175 psia (1.21 MPa)	3%	0	7	2	0	–25	–6	0	–39	–18			
	4%	0	1	0	0	–13	–10	0	–22	–14			
	5%	0	2	1	0	–11	–7	0	–26	–17			
225 psia (1.55 MPa)	3%	0	12	12	0	–20	–13	0	–46	–16			
	4%	0	18	17	0	–9	–4	0	–31	–14			
	5%	0	6	3	0	–9	1	0	–39	–14			

[a] $[(P, T)_{\text{inlet}}$ = [75 psia (0.52 MPa), 500 °F (533 K)], [125 psia (0.86 MPa), 625 °F (603 K)], [175 psia (1.21 MPa), 725 °F (658 K)], and [225 psia (1.55 MPa), 790 °F (694 K)].

[b] $\Delta T < 0$ implies cooler liner temperature.

3% ΔP and gives a better picture for the heat performance of the fuels. Table 2 outlines all the average temperature differences (convective and radiation cooling) for all testing conditions.

The overall trend shows that at F/A = 0.010, both the blend and the FT fuel generally run at higher temperatures than JP-8 for all pressure values. As the F/A increases, the 50:50 blend and the FT fuel temperatures decrease, ending with cooler operating temperatures relative to JP-8 at the 0.020 ratio. With respect to the increasing F/A, there is a larger deviation in the temperature performance of the FT and 50:50 fuels. At the higher F/A, the FT fuel runs at temperatures cooler than both the JP-8 and the blend, illustrating that at these higher F/A values, the impact of the FT performance within the blend decreases and JP-8 performance dominates. This would mean that at high F/A, the FT fuel would decrease liner temperatures relative to the JP-8 and the 50:50 blend and could increase component life within the combustor and yet not the turbine. Also, greater temperature differences are shown for higher inlet pressures and temperatures.

Combustion Exhaust Rake Temperature

The exhaust plane temperature trends are illustrated in Fig. 4. These temperature profiles represent data-averaged temperature values collected through use of a temperature probe (rake) placed in the exhaust plane of the combustor. In these data, the signal from the top thermocouple was lost. For all data sets, there is a monotone increase in the exhaust plane temperature as F/A is increased. The increase in %ΔP also creates an increase in the temperature. At higher percent combustor pressure drop values and higher F/A, the FT fuel tends to run at higher exhaust temperatures compared to JP-8 and the blend, which also gives slightly higher temperatures. Upon further analysis, as F/A increases, the FT fuel, while at higher exhaust plane temperature, generally has less effect on the performance of the blend compared to that of JP-8. There is not a large temperature difference between the fuels at the higher %ΔP and F/A ($\Delta T = T_{\text{fuel blend}} - T_{\text{JP-8}}$ = ~20–50 °F (11–27 °C)) where there are larger differences at higher inlet temperatures and pressures; however, a small change in temperature can have major impact on the turbine life and efficiency, so these effects must be taken into consideration when selecting an alternative turbine engine fuel.

Plotting the combustor exhaust rake temperature differences versus the inlet pressure and F/A (Fig. 5) displays a minimum, above which the variables have a positive effect on the combustor performance of alternate fuels over JP-8 fuels.

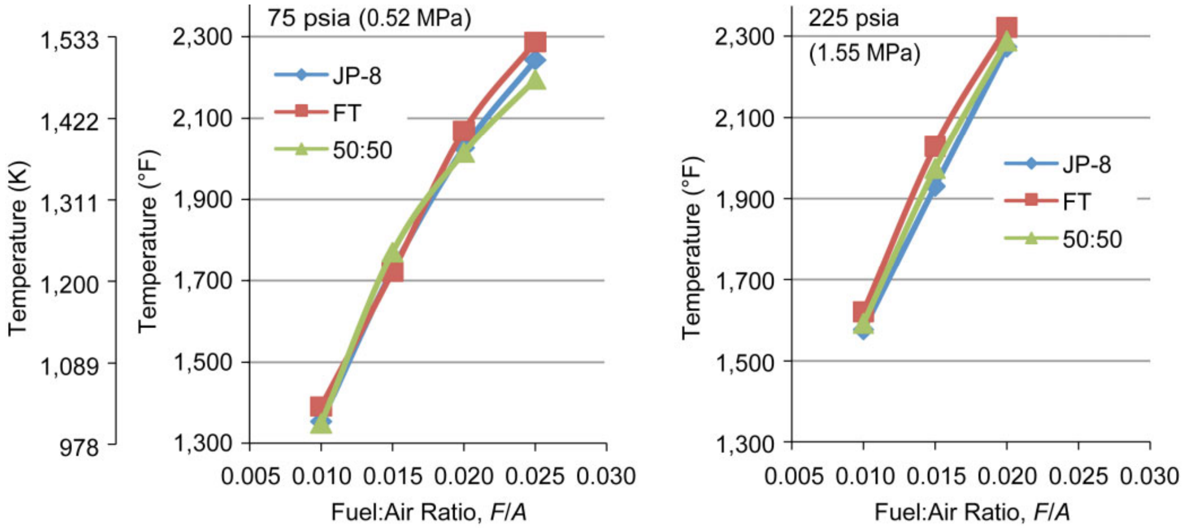

Fig.4 Variation of exhaust plume temperatures with percent fueling as a function of F/A for $(P, T)_{inlet}$ = [75 psia (0.52 MPa) and 500° F (533 K)] and [225 psia (1.55 MPa), 790 °F (694 K)], at 3% ΔP.

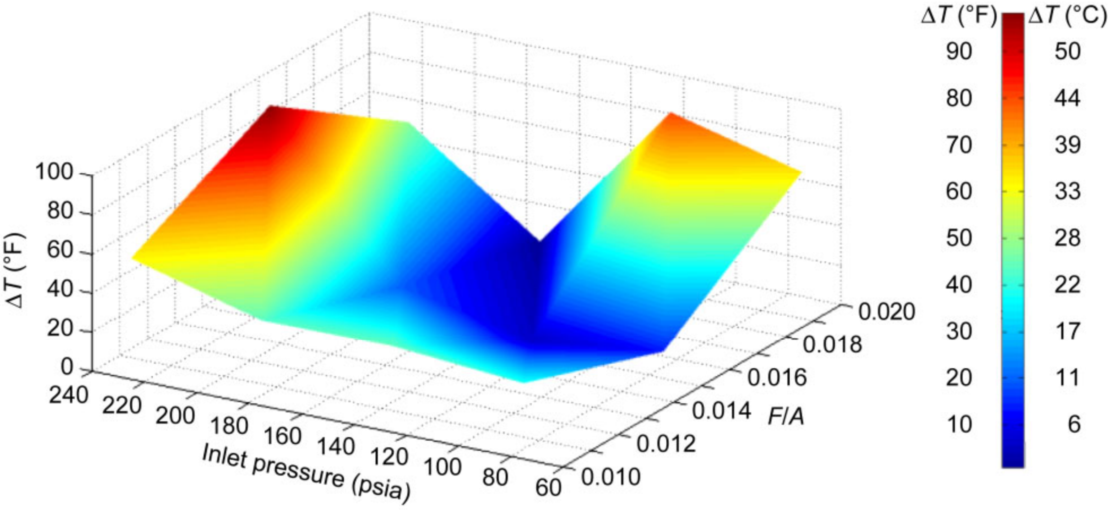

Fig.5 Combustor exhaust rake temperature differences ($\Delta T = T_{\text{fuel blend}} - T_{\text{JP-8}}$, °F) versus inlet pressure and F/A for 3% ΔP for 100% FT fuel, showing pressure and F/A combinations that improve performance (warmer colors) (1 MPa = 145 psia).

Performing the same analysis for all %ΔP conditions for both the 100% and 50:50 FT fuel temperature difference data, it is clear that increasing the inlet pressure increases the temperature differences of the FT fuel compared to JP-8. There also appears to be a peak in performance around 3–4% ΔP for the alternate fuel in relation to the performance of JP-8 (illustrated in Fig. 6).

Calculated flame temperature data are outlined in Fig. 7 for 225 psia (1.55 MPa) at 3% ΔP. As the inlet pressure and temperature is increased, there is a small increase in the flame temperature. The same trend is displayed with increasing %ΔP, although %ΔP does not seem to affect the temperature differences between the fuels to a significant extent. The %ΔP trend is more pronounced than that of the changing inlet pressure and temperature, especially when increasing F/A. At higher F/A, there is a greater difference in flame temperatures between the fuels. The FT generally had higher flame temperatures than the JP-8, and the 50:50 blend temperatures fell temperatures between the FT and the JP-8 fuel. These trends are also displayed in Table 3, which contains the flame temperature differences between JP-8 and the FT fuels. No significant trend determining whether the FT or JP-8 performance had the dominant role in the flame temperature performance of the 50:50 blend was found.

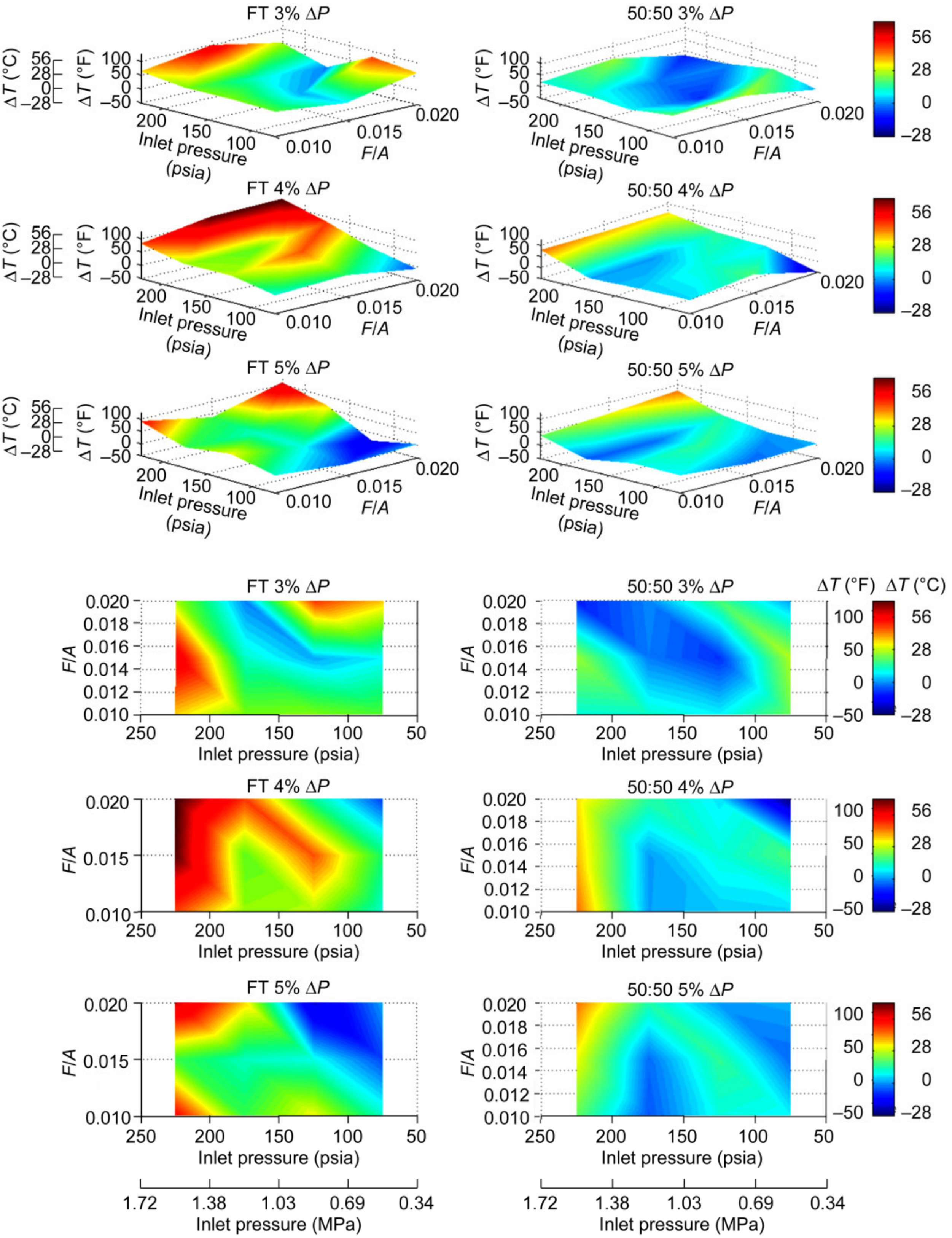

Fig.6 Combustor rake temperature differences ($\Delta T = T_{\text{fuel blend}} - T_{\text{JP-8}}$, °F) versus inlet pressure and F/A for 3%, 4%, and 5% ΔP for 100% and 50:50 FT fuel with respect to JP-8, showing pressure and F/A combinations that improve performance (warmer colors) [ΔT (°F) = 1.8ΔT (K)] [1 MPa = 145 psia].

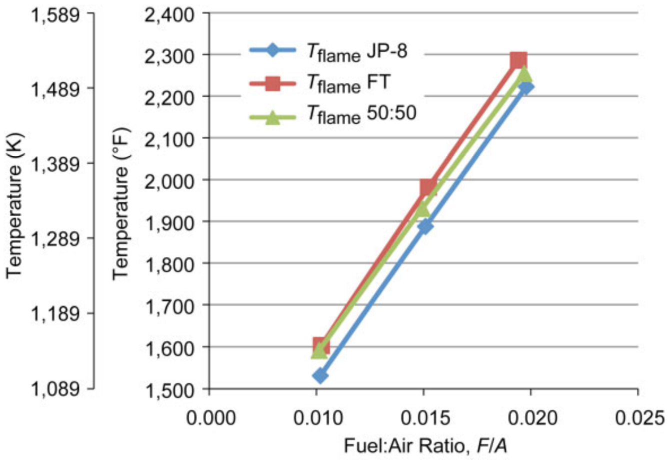

Fig.7 Calculated flame temperature (T_{flame}) variation with F/A and fuel composition for $(P,T)_{inlet}$ = [225 psia (1.55 MPa), 790 °F (694 K)] at 3% ΔP.

Table 3 Flame temperature differences ($T_{fuel\ blend} - T_{JP\text{-}8}$) (°F) for $(P,T)_{inlet}$ = [225 psia (1.55 MPa), 790 °F (694 K)]

Fuel	F/A	%ΔP 3%	4%	5%
FT –JP-8	0.010	73 (41)	107 (59)	71 (39)
	0.015	94 (52)	84 (47)	63 (35)
	0.020	34 (19)	105 (58)	90 (50)
50:50 –JP-8	0.010	55 (31)	90 (50)	33 (18)
	0.015	43 (24)	41 (23)	52 (29)
	0.020	–3 (–2)	42 (23)	70 (39)

Values in parenthesis are in Kelvins.

Conclusions

The data and analysis of combustor sector alternate fuel performance of Combustor A show lower average liner temperatures and higher flame and average combustor outlet temperatures with increasing FT relative to JP-8+100 fueling. The latter affects turbine efficiency and blade/vane life and may be due to the higher heat of combustion of the FT fuel per unit mass. Thus, the engine would not be running at higher F/A. A more accurate way to assess how these outlet temperatures will affect the turbine life would be to look at the pattern factor of the exhaust temperatures.

Sidewall temperatures depend mainly on F/A for performance decreasing in temperature from the FWD to MID and increasing in temperature from the MID to AFT. The unwrapped liner temperature data show that the blend and the FT fuel run hotter than JP-8 at lower F/A, but cooler at F/A above ~0.015. At the higher F/A values the FT fuel temperature differs moreso from the JP-8 than the blend. Peak liner temperatures also increase with increasing F/A and %ΔP but seem unaffected by the type of fuel blend to a significant extent. Lower liner temperatures result from decreased radiative heat transfer from reduced aromatic content.

The 100% FT fuel tends to run at higher exhaust temperatures compared to the JP-8 and 50:50 blend fuels, with a similar trend for flame temperature. Overall, increasing F/A and %ΔP increases the thermal performance of the combustor, which will almost always occur unless there is a decrease in the efficiency of combustion.

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