Predicted TF41 Performance with the AGARD Research Fuel

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Calculations are presented to predict the performance of an alternative fuel in a conventional gas turbine combustor. Existing data for fuel effects on the Detroit Diesel Allison TF41 combustor, a can-annular burner, are correlated with the semi-empirical characteristic time model. The correlations are used to predict the ignition, stability, and combustion efficiency performance of a proposed alternative fuel, the AGARD Research Fuel, in the TF41 combustor. Compared to standard JP-4 and JP-8 fuels, the alternative fuel will provide similar combustion efficiency levels, reduced flame stability, and significantly degraded ignition performance.

Nomenclature

a	= empirically selected weighting factor
b	= pre-exponential factor
C_{pg}	= gas phase specific heat
d_{comb}	= combustor diameter
d_0	= Sauter mean diameter
d_q	= spark kernel diameter
E	= activation energy
E_{sp}	= spark energy
l_{co}	= mixing length for CO
l_q	= quench length
m_f	= fuel flowrate
Ma	= flight Mach number
R	= universal gas constant
T_{exh}	= combustor exhaust temperature
T_{in}	= combustor inlet temperature
T_η	= temperature for combustion efficiency kinetics
$T_{\phi=1}$	= stoichiometric adiabatic flame temperature
V_{ref}	= combustor reference velocity
β	= evaporation coefficient
ΔP	= fuel injector pressure drop
η_c	= combustion efficiency
ν_f	= viscosity
ρ_g	= gas phase density
σ_f	= surface tension
τ_{eb}	= droplet evaporation time
τ_{hc}	= kinetic time for ignition and lean blowoff
τ_{sl}	= mixing time
τ_η	= kinetic time for combustion efficiency
ϕ	= equivalence ratio

Introduction

THE introduction of alternative fuels and the relaxation of fuel property specifications of current fuels are areas of concern for the gas turbine community because changes in fuels or fuel properties raise questions regarding engine performance. Although the importance of specific fuel properties to the performance of an engine may be known qualitatively (e. g., front end boiling points on ignition and carbon to hydrogen ratio (and/or aromatics) on soot),[1-3] quantitative understanding for determining the effects of new and previously untested fuels is often lacking. In this paper, calculations are presented for gas turbine engine performance predictions in the areas of ignition, lean blowoff, and combustion efficiency for an alternative fuel. Calculations are also made for standard fuels for which performance data are available to provide a comparison with the alternative fuel, and to establish the validity of the predictions.

The combustion system for which the predictions are made is the Detroit Diesel Allison TF41. The TF41 is a turbofan engine which features a ten-can can-annular combustion chamber; a schematic of a single can is shown in Fig. 1. Fuel is introduced with ten dual-orifice pressure atomizing nozzles and ignition is achieved with surface discharge plugs located in two cans. Further details of the engine can be found elsewhere.[4] The TF41 experimental data used in this paper were obtained from single-can rig tests by Vogel et al.[4,5] In their study two fuels, JP-4 and JP-8, were used and blends of each of these fuels with different components were also tested to provide a total of twelve test fuels. Typical run conditions for the TF41 fuel tolerance tests are shown in Table 1.

Characteristic Time Model

The characteristic time model will be used to predict the performance of the TF41. This model was selected for two primary reasons: 1) it is relatively simple to employ; the important physical processes are determined and computed through times (evaporation, kinetic and mixing, for example) that are representative of the processes, and 2) this approach has previously been shown to work well for correlating emissions data, ignition and lean blowoff limits, and combustion efficiency data from both fundamental experiments and actual gas turbine hardware.[6-9]

Table 1 Typical TF41 combustor test conditions

	Airflow, kg/s	Inlet temperature, K	Pressure, kPa
Ignition and lean limit			
Sea level idle	1.1	420	290
Ma = 0.6, 3.05 km	0.87	280	150
Ma = 0.6, 10.7 km	0.55	280	93
Ma = 0.6, 12.2 km	0.46	280	79
Ma = 0.6, 15.2 km	0.35	280	62
Combustion efficiency			
Idle	0.96	430	290
Cruise	1.6	580	510
Sea level dash	5.1	740	1820
Sea level takeoff	5.0	760	1840

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With this semi-empirical modeling technique, the phenomenon of interest is considered to occur as the result of the competition of various processes In the oxidation of CO, for example, the rate (inverse time) of CO consumption as determined by chemical kinetics can be compared to the length of duration of the combustible mixture within a reacting region of the flow. Thus, the relative values of the kinetic and mixing times will yield information on the levels of CO emission

The times of importance for this work are listed in Table 2 The turbulent mixing time is estimated by a length scale divided by the combustor reference velocity The evaporation time is given by the square of the Sauter mean diameter (estimated from empirical relations) divided by the evaporation coefficient Finally, kinetics are taken into account by Arrhenius expressions The similarities and differences of these times for ignition, lean blowoff, and combustion efficiency will be described, along with the model formulations for each case, in the following sections

Ignition

For ignition to occur in a gas turbine engine, the rate of heat release (controlled first by the evaporation of the fuel and then by chemical kinetics) must exceed the heat loss rate (controlled by turbulent mixing) from the spark kernel Therefore, in terms of the characteristic time model, the ignition limit is given by

$$\tau_{s\ell} \sim \tau_{hc} + a\tau_{eb}/\phi \qquad (1)$$

where the proportionality and the constant weighting factor, a, are necessary because the times are simply estimates of the processes involved and are not expected to be quantitatively exact.

As noted in Table 2, the length scale for ignition is the spark kernel diameter, defined as the diameter of a sphere which would be heated to the stoichiometric adiabatic flame temperature by the spark energy,

$$d_q = \left[\frac{E_{sp}}{(\pi/6)\rho_g C_{pg}\Delta T_{\phi=1}}\right]^{1/3} \qquad (2)$$

where the energy at the spark was estimated to be 1 5 J Also from Table 2, the droplet evaporation time is computed from the "d^2 law"[10] and the drop size is calculated from an empirical equation for a single orifice pressure atomizing nozzle given by Jasuja[11] as

$$d_0 = \frac{8\ 88\sigma_f^{0.6}\nu_f^{0\ 16}\dot{m}_f^{0.22}}{\Delta P^{0.43}} \qquad (3)$$

where the drop diameter is given in μm, surface tension in dyne/cm, viscosity in cs, fuel flowrate in kg/h, and pressure drop in atm Although the TF41 employs a dual-orifice nozzle, for the low fuel flowrates of ignition (and lean blowoff) the majority of the fuel is introduced to the combustor through the pilot nozzle and a single orifice equation used to estimate drop size suffices For the combustion efficiency data, the fuel enters through both the pilot and main nozzles; Eq (3) is used to estimate d_0 for both nozzles, and a combined d_0 can be found from a mass weighted average of the pilot plus the main injector

Dividing the evaporation time by the equivalence ratio takes into account the fact that adding more fuel (more drops) decreases the time it takes for a given amount of fuel to reach the vapor phase Finally, for the kinetic time, $b = 10^{-5}$, $E = 26{,}100$ cal/mole, and ρ_g is the gas phase density in kg/m^3 For details on the derivations of these terms, see Peters [12]

The TF41 ignition data include sea level start and altitude relight data at a flight Mach number of 0 6. These data are used to calculate the terms in Eq (1) and the results are shown in Fig 2 where a least-squares fit line and one standard deviation about that line are included. (The weighting factor of 0 021 was selected from previous work [12]) The fit is statistically good ($r > 0\ 9$) although the correlation does not pass through the origin The large intercept on the ordinate has been observed by others[13] and may be caused by significant amounts of energy not participating in the ignition process due to losses in the ignition circuit One other point of interest is that the equivalence ratio (at the spark gap) that appears in Eq (1) and in the kinetic time was previously found to be constant for can-type combustors (and assumed equal to one). This approach is verified here because no correlation could be found by letting ϕ vary with the primary zone equivalence ratio; Fig. 2 is a result of setting the equivalence ratio at the spark gap equal to one

The best fit line separates the figure into two regions: ignition and no ignition If an engine is operating in the upper left-hand portion of the figure, ignition is possible The ignition limit is approached by moving horizontally (in

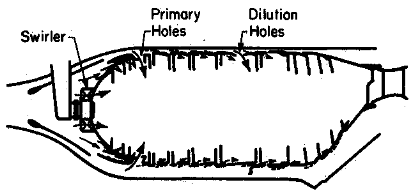

Fig 1 TF41 combustor schematic [4]

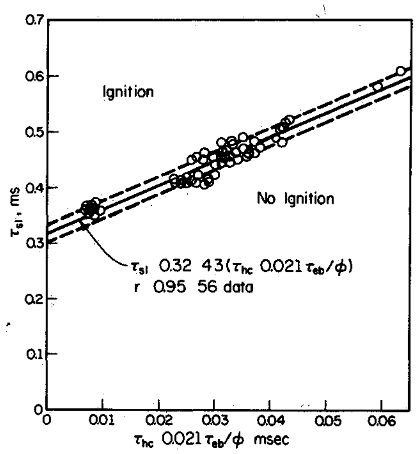

Fig 2 TF41 ignition correlation (data from Ref 4)

Table 2 Characteristic times

		Definitions		
Time	Meaning	Ignition	Lean blowoff	Efficiency
$\tau_{s\ell}$	Mixing	d_q/V_{ref}	l_{co}/V_{ref}	l_{co}/V_{ref}
τ_{eb}	Evaporation	d_0^2/β	d_0^2/β	d_0^2/β
τ_{hc}	Kinetics	$b\exp(E/RT_{\phi=1})/\rho_g\phi$	$b\exp(E/RT_{\phi=1})/\phi$	
τ_η	Kinetics			$b\exp(E/RT_\eta)/\phi$

Table 3 Fuel properties

Property	JP 4[a]	JP 8[a]	ARF[b]
Density at 21 C, g/cm^3	0 760	0 807	0 800
Viscosity at 25 C cs	0 98	1 94	3 75
Surface tension at 21 C dynes/cm	23.7	26.9	26 3
Hydrogen weight, %	14 4	13 9	13 2
Lower heating value, MJ/kg	43 5	43 1	43
10% boiling point K	360	451	478
50% boiling point, K	438	499	525

[a] Fuel properties listed are for the ignition and lean blowoff tests The fuels for the combustion efficiency tests had slightly different properties See Ref 4 for details [b] Properties not included in the ARF specification were estimated

creasing the evaporation time by increasing drop size or decreasing volatility, for example) or vertically (decreasing the mixing time by increasing the reference velocity or decreasing the ignition energy)

Based on the ignition correlation in Fig 2, ignition limit calculations can now be made This paper will focus on the three fuels listed in Table 3. The JP 4 and JP-8 fuels will be included in the calculations to act as a comparison of the model with available data and as a comparison to the predicted performance of an alternative fuel, the AGARD Research Fuel (ARF) Generally speaking, JP 4 is the "lightest" fuel as indicated by the lower boiling points and viscosity ARF is a representative of possible future alternative fuels with higher boiling points, higher viscosity, and lower hydrogen content ARF properties were defined by the Propulsion and Energetics Panel Working Group 13 as a proposed test fuel

The fuel properties in Table 3 were used in conjunction with the correlation of Fig 2 to determine the percent decrease in drop size required to achieve ignition for JP-8 and ARF compared to the JP-4 baseline fuel The results are shown in Fig 3 As in all the predictions for this paper, the sea level calculations were performed for idle inlet conditions and the altitude calculations for a Mach number of 0 6 The graph clearly indicates that the atomization quality has to improve for the "heavier" fuels to ignite In other words, to obtain the evaporation rate required for ignition, the drop sizes of JP-8 and ARF must decrease to compensate for their lower volatilities The improvements required in atomization quality is largest at the idle condition and nearly constant at the various altitudes

The improvement in atomization indicated in Fig 3 is substantial This is illustrated in Fig. 4 where the predicted primary zone equivalence ratio required for ignition (assuming all the fuel flows through the pilot nozzle which would give the best atomization) is plotted against altitude The standard deviation of the correlation in Fig 2 was used to determine the "error bars" on the JP-4 calculations This provides an indication of the accuracy of the model Since the TF41 employs a pressure atomizing nozzle, fuel flow must increase in order to decrease drop size. In addition, JP-8 and ARF are more viscous than JP-4 and this requires a further increase in fuel flow to reduce the drop size The net result is that the fuel flowrate required for ignition with an alternative fuel such as ARF is significantly higher than the flowrate required for a standard fuel such as JP 4 In fact, the fuel flowrate required to achieve the drop sizes and primary zone equivalence ratios required for ARF is so high that it would not be reached in the standard ignition sequence This indicates that, for the TF41 to accommodate ARF and retain the same ignition capabilities, changes in the fuel injection system would be required.

Lean Blowoff

Flame stabilization (or lean blowoff) and ignition are similar phenomena In both cases, a fuel and air mixture must be heated so that the fuel evaporates, mixes with the air, and

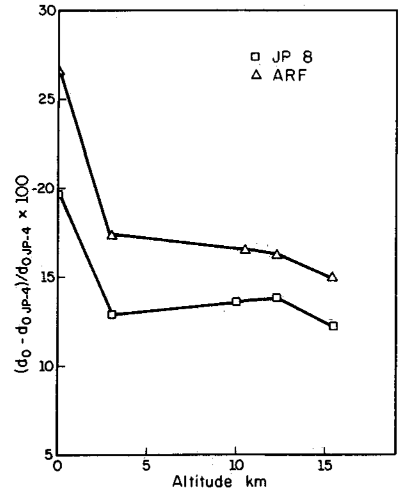

Fig 3 Predictions of the decrease in drop size required for ignition capabilities equivalent to JP 4

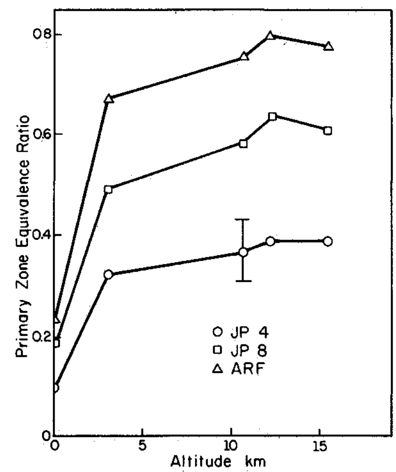

Fig 4 Predictions of primary zone equivalence ratio required for ignition

chemical reactions begin at a rate sufficient for establishing a flame The difference between ignition and flame stabilization is the energy source which initiates combustion, hot recirculating gases for flame stabilization, and a spark for ignition Consequently, it is not surprising that the formulation of the characteristic time model for lean blowoff is very similar to the ignition model The lean blowoff model is

$$\tau_{sl} \sim \tau'_{hc} + a\tau'_{eb} \tag{4}$$

where the definitions of the terms can be found in Table 2

The length scale for the mixing time is selected as the length scale for CO emissions, l_{co}, defined by

$$l_{co} = [d_{comb}^{-1} + l_q^{-1}]^{-1} \tag{5}$$

where the quench length is chosen as the axial distance from the fuel injector to the primary air addition jets For the TF41, l_q is 6 cm which, combined with a combustor diameter of 13 2 cm, gives a length scale for CO of 4 13 cm The droplet lifetime is defined as before, and for the kinetic time the pre exponential factor is 10^{-4}, the activation energy is 21,000 cal/mole, and the equivalence ratio is evaluated as the primary zone equivalence ratio The "prime" denotes that the times are multiplied by the temperature ratio, $T_{\phi=1}/T_{in}$ This accounts for the acceleration of the flow due to the heat release in the primary zone and is included on the right hand side of the equation to remove chemistry effects from the mixing time For further details, see Ref 8

The TF41 lean blowoff data were obtained at the same inlet conditions as the ignition data The terms in Eq (4) were calculated from the blowoff data and are shown in Fig 5 Also included in this figure are data from two single can combustors, the Detroit Diesel Allison T63 and the Avco-Lycoming AGT 1500 The additional data were included because of the rather narrow range of the TF41 data With the weighting factor of 0 033 chosen to give the best fit, the correlation is not as good as the ignition correlation, but certainly statistically significant The weighting factor and slope shown in Fig 5 are different than those found elsewhere [8] but this is to be expected because the evaluation of fuel properties in this paper was based on the 10% boiling point rather than the 50% point used by Leonard and Mellor [8] The 10% point was selected to make the calculations consistent with the ignition work where the lighter fractions of the fuel are known to be more important in the ignition process While Fig 5 indicates that the 10% point can also be used for lean blowoff the previous correlation,[8] based on the 50% point, may be somewhat better (lower intercept on the ordinate, but still not zero)

Figure 5 is interpreted in a manner similar to Fig 2 The regions of stable and unstable operation of the combustor are separated by the best fit line which represents the lean limit From a stable operating point, one moves toward the limit by decreasing the primary zone equivalence ratio (increasing τ'_{hc}) or decreasing the fuel volatility (increasing τ_{eb}) for example Increasing the reference velocity would result in a decrease in τ_{sl} and again the lean limit would be approached

Based on the correlation in Fig 5, the primary zone equivalence ratios at blowoff were predicted for the TF41 and the three fuels listed in Table 2 The results are presented in Fig. 6 Although $\phi = 1$ is used for the calculation of the kinetic time the primary zone equivalence ratio can still be predicted because of the appearance of the fuel flowrate in the drop sizing equation. Included in the figure are the actual data from the TF41 for JP 4 and JP 8 The trends of the model are validated by the data, although in some cases there is disagreement between the measured and calculated values Based on the scatter of the correlation in Fig 5, this is to be expected

One can see that the heavier fuels are less stable (require a higher primary zone equivalence ratio) than the lighter fuels. This difference is most pronounced at the higher altitudes with little difference occurring at the sea level condition Based on these results, an alternative fuel with properties similar to ARF will be significantly less stable at high altitude although the effect of fuel type on lean blowoff is not as large as it is for ignition

Combustion Efficiency

When evaporation effects are negligible, the process that controls gas turbine combustion efficiency is the mixing of CO and hydrocarbons out of the hot shear layers before complete combustion occurs and into cooler regions of the combustor where they are quenched In terms of the characteristic time model, this means that combustion inefficiency should be proportional to the ratio of the kinetic and mixing times,

$$(1-\eta_c) \sim \tau_\eta / \tau_{sl} \tag{6}$$

When evaporation is slow Leonard argued that the longer life (and trajectory) of the drops can cause the addition of more CO and hydrocarbons into the cooler quenching regions [9] With this additional contribution to combustion inefficiency, the model becomes

$$(1-\eta_c) \sim (\tau_\eta / \tau_{sl}) / (1 + a\tau_{eb} / \tau_{sl}) \tag{7}$$

The mixing and evaporation times are shown in Table 2 to be the same as those used for lean blowoff although for combustion efficiency the fuel properties are evaluated at the 50% boiling point For the kinetic time the pre exponential factor is 10^{-2} the activation energy is 4500 cal/mole, and the temperature is a weighted average between the inlet and exhaust,

$$T_\eta = 0\ 9T_{\text{in}} + 0\ 1T_{\text{exh}} \tag{8}$$

Details on the derivations of these terms can be found elsewhere [9]

With combustion efficiency data from Vogel et al [4] at four run conditions (idle, cruise, dash, and takeoff) and Eq (7), the correlation shown in Fig 7 was generated for the TF41 The weighting factor of 0 05 was obtained from Leonard[9] and the slope of the correlation, 3.4, compares favorably with the slope of 3 2 found by Leonard[9] for three other engines Again, scatter is evident about the best fit line but the correlation coefficient indicates a statistically significant fit

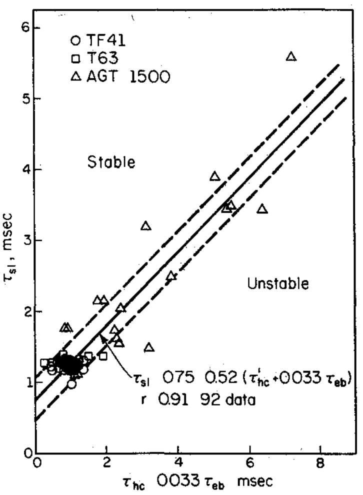

Fig 5 Lean blowoff correlation for three combustors (data from Refs 4, 8, 14, and 15)

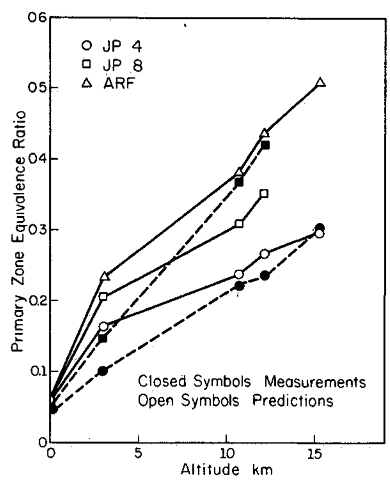

Fig 6 Predicted and measured lean limit primary zone equivalence ratios (measurements from Ref. 4)

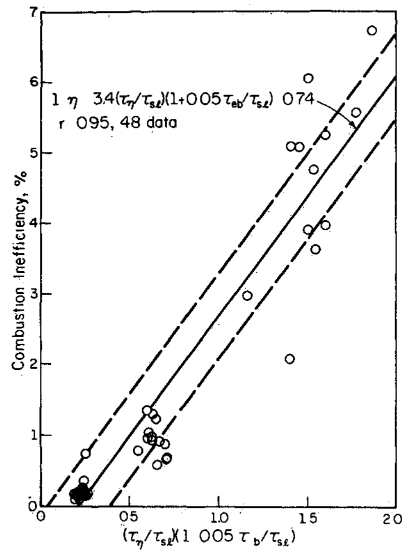

Fig 7 TF41 combustion efficiency correlation (data from Ref 4)

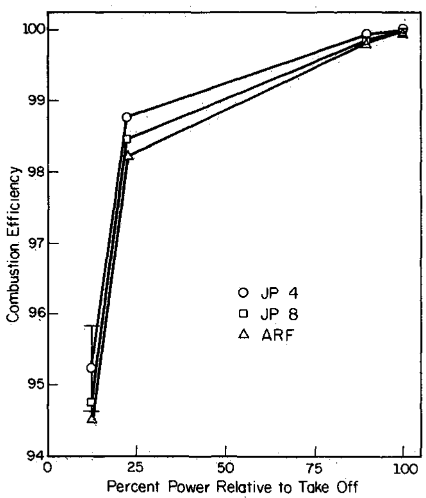

Fig. 8 Predictions of combustion efficiency

Although a second order equation through the data would appear to give a better fit, at present the linear combustion efficiency correlation used by Leonard[9] will be retained for consistency The use of a second order fit to achieve a better correlation of the data should be examined with referral to the previous data correlated by Leonard[9] for completeness

Based on the correlation in Fig 7, combustion efficiency predictions were made for ARF and are presented in Fig 8 with calculations for JP-4 and JP 8 As before, the "error bar" indicates the range of predicted efficiency based on one standard deviation about the correlation Above idle conditions the efficiencies are quite high and little difference is exhibited with fuel type, although ARF is predicted to have the lowest efficiency At idle conditions the separation of fuels is more pronounced, indicating the increased influence of slower evaporation at the low power point of the "heavier" ARF In general, the effect of an alternative fuel with properties similar to ARF on combustion efficiency in the TF41 is small, especially at high power conditions

Conclusions

Illustrated in this paper were the predictions of the performance of an alternative fuel in a conventional gas turbine combustor These predictions were obtained from a relatively simple model and the predictions were supported by the favorable comparison of performance calculations for existing fuels for which data were available

The results indicate that, for this particular engine and alternative fuel ignition is most sensitive to fuel changes, lean limit stability performance is degraded to a lesser degree, and combustion efficiency is only modestly influenced, in agreement with the conclusions of Vogel et al.[4] In particular, it was shown that fuel injection modifications would be required to retain good ignition characteristics with the alternative fuel

The quantitative changes in performance as a function of fuel type presented in this paper can also be predicted in other engines for other alternative fuels to provide input into future combustor and fuel type considerations

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