Effects of Alternative Fuels on Ignition Limits of the J85 Annular Combustor

T. A. Jarymowycz* and A. M. Mellor†
Drexel University, Philadelphia, Pennsylvania

Recent studies on ignition limits in gas-turbine engines have focused on alternative fuels and their effects. New tests reported here at the Naval Air Propulsion Center (NAPC) utilized five fuels and systematic increments of combustor inlet conditions to establish data for the General Electric J85-21 gas-turbine combustor. A characteristic time model for ignition was used to scale inlet conditions to those used by GE and to reduce the data. The resulting correlation, including both NAPC and GE data, is rearranged to predict loss in engine altitude for relight with a fuel more viscous than JP-4.

Introduction

RECENT efforts to predict the limits of ignitability in gas-turbine engines have been focused on alternative fuels and their effects. The utility of using characteristic time models for correlating gas-turbine emissions and combustor efficiency, as well as the limits of ignition (cold start and altitude relight) and lean blowoff using standard gas-turbine fuels has been demonstrated.[1,2] The present research will examine the utility of the spark ignition characteristic time model with the General Electric J85-21 gas-turbine combustor burning alternative fuels.

Manufacturer's ignition data[3] from a J85 combustor were previously correlated,[4] and the results are shown in Fig. 1. Note that these tests are performed at discrete combustor inlet conditions leading to groups of data such as those shown in the figure. New tests reported here used systematic increments of the inlet conditions in order to obtain a full representation of the possible operating conditions during ignition. Further model validation is required if the ignition model is eventually to be used as a predictive tool.[4]

Background

The spark ignition model is based on the premise that the spark energy heats an initial volume of fuel vapor and air such that the heat generated within this volume is greater than the heat lost. In a conventional gas-turbine combustor employing a recirculation-held, spray diffusion flame, the physical processes responsible for ignition may be expressed as three characteristic times.[5,6] Heat generation is limited by droplet evaporation τ_{eb} and vapor-phase kinetics τ_{hc}. At the ignition limit, the sum of these times equals the turbulent mixing time τ_{sl}. This is represented by the algebraic expression

$$\tau_{sl} \sim \tau_{hc} + a \cdot \tau_{eb} \qquad (1)$$

The proportionality and constant weighting factor a is required because these times are representative of only the actual physical processes. The times are not expected to be quantitatively exact. Although definitions for calculation of these times have been presented elsewhere (e.g., Ref. 6), they are repeated to expedite the discussion below on design of the experimental test matrix.

The turbulent mixing time is estimated as a length scale divided by a velocity within the combustor

$$\tau_{sl} = d_q / V_{\text{ref}} \qquad (2)$$

The length scale for ignition is the spark kernel or quenching diameter d_q, the small volume of air and fuel vapor heated to the stoichiometric adiabatic flame temperature $T_{\phi=1}$ by the minimum ignition energy $E_{\min}$.

$$d_q^3 = \frac{E_{\min}}{(\pi/6)\rho_g c_{pg} \Delta T_{\phi=1}} \qquad (3)$$

In Eq. (3), ρ_g is the gas density, and c_{pg} is the specific heat of the gas. The velocity is that at the spark gap; however, the reference velocity V_{ref}, based on maximum combustor cross-sectional area, is substituted because it is proportional to the spark-gap velocity and is known.

The droplet evaporation term is determined by fuel volatility and Sauter mean diameter d_0. It is evaluated using the d^2 law of Godsave[7]

$$\tau_{eb} = d_0^2 / \beta\phi \qquad (4)$$

where β is the evaporation coefficient and ϕ is the equivalence ratio in the spark gap.[5]

The kinetic time is derived for the ignition of lean fuel and air mixtures.[5,6] For hydrocarbon oxidation

$$\tau_{hc} = [b\exp(E/RT_{\phi=1})] / \phi\rho_g \qquad (5)$$

where b is the preexponential factor (10^{-5} ms g cm^{-3}), E the activation energy, and R the universal gas constant. The activation energy value of 26,100 cal/mole suggested by Fenn[8] is used here because it adequately represents a wide range of hydrocarbon fuels.[6]

The ignition modeling approach presented here was verified using quiescent fuel sprays by Peters and Mellor,[5] and by Ballal and Lefebvre[9] with flowing mixtures in an experimental test rig. The application of this model to gas-turbine combustors was performed by Peters and Mellor,[6,10] Peters,[11] and Moses and Naegeli.[12]

The combustor available for testing in this program is the annular General Electric J85. Manufacturer's ignition data[3] from the J85 were correlated by Naegeli et al.[4] and Moses and Naegeli.[12] Seven fuels were used in a combination of cold-start and altitude-relight tests.[3] The correlated results[4,12]

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*Undergraduate, Department of Mechanical Engineering and Mechanics; presently Graduate Research Assistant, Department of Mechanical Engineering, The Pennsylvania State University.

†Hess Chair Professor of Combustion, Department of Mechanical Engineering and Mechanics.

are shown in Fig. 1 with

$$\tau_{sl} = 2.00(\tau_{hc} + 0.021 \cdot \tau_{eb}) + 0.00 \quad (6)$$

and $\sigma_y = 0.063$. The region to the left of the correlated line represents ignition where fuel droplets evaporate and ignite in time sufficient to sustain a stable flame. The region to the right is the region of no ignition, with the correlated line representing the ignition limit.

Although the results in Eq. (6) are satisfactory (correlation coefficient $r = 0.88$), the linearity of the model remains untested. For example, the data in Fig. 1 are collapsed into three distinct groups corresponding to altitude relight near the origin and cold start in the upper-right corner, so the linearity between these groups remains in question. The grouping results from manufacturers testing at discrete combustor inlet conditions. One of the objectives of this paper is to vary the inlet conditions more continuously and systematically.

The slope of the correlated line is also important. If similar slopes were obtained for all conventional combustors, then an equation like (6) could be used to predict cold-start and altitude-relight limits for new engines still in the design phase (for which no data exist) or for older engines operating on new fuels.[11] However, in an extensive study involving data from 12 different engines,[12] the individual engine correlations fell into three groups, with slopes in Eq. (6) of approximately 1, 2, and 4. It was not possible to clarify any correspondence between engine and combustor design and operation and slope.[12] Thus, either original uniformity of slope for three engines[10] is fortuitous, or the above characteristic time definitions must be revised. In either case, further model validation is required, which was the second intent of the present study. The experimental portion of this validation was conducted at the Naval Air Propulsion Center (NAPC) in Trenton, New Jersey.

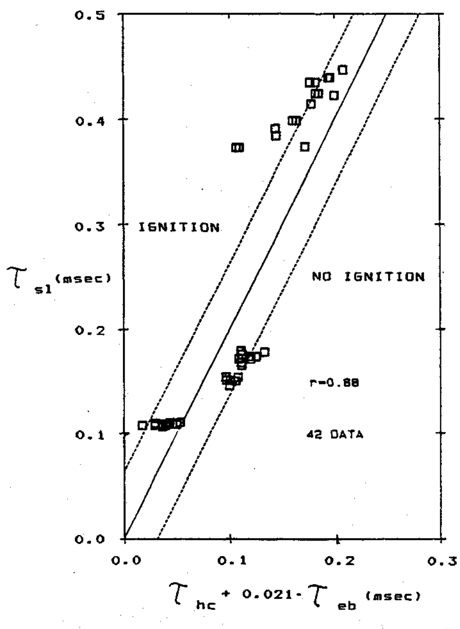

Fig. 1 Characteristic time model correlation of manufacturer's J85 ignition data.[4] Equation of the best-fit line: $\tau_{sl} = 2.00$ $(\tau_{hc} + 0.021 \cdot \tau_{eb}) + 0.00$; $\sigma_y = 0.063$; 42 data.

Experimental Apparatus

The NAPC Hot Gas Facility is shown schematically in Fig. 2. Two T56 engines drive a modified T56 compressor, which provides a maximum airflow of 13.5 kg/s at 7 atm and 530 K constant discharge temperature. The test section is currently a 0.51-m-i.d. pipe, which houses a J85-21 annular combustor. Water injection is used to cool the combustor exhaust gases to acceptable levels. A bleed valve upstream and back-pressure valve downstream of the test section control its airflow and pressure. The airflow through the combustor and test section is monitored by the pressure drop across a calibrated screen, as shown in Fig. 2. Appropriate pressures and pressure drops are sensed in the test section with PSI transducers. The combustor exhaust-gas temperatures were monitored by six exit plane thermocouples equally spaced on an area-averaged basis between the inner and outer annulus. The thermocouples were mounted on a rake, which could be rotated around the combustor centerline.

The fuel system presently provides a maximum flow of 1590 kg/h of jet fuel at 100 atm at ambient temperature. Test fuel temperature was monitored just upstream of the injector manifold. Five fuels with properties listed in Table 1 were used for the ignition tests.

The J85 annular cross section is shown in Fig. 3. Compressor discharge air is slowed by the diffuser. The airstream then splits into three distinct paths. One path flows along the outer annulus, another along the inner annulus, and the third into an air scoop, which provides air to a radial swirler in the combustor dome. The combustor's outer diameter is 0.39 m, the inner diameter is 0.23 m, and the annulus height is 0.08 m.

The only igniter in the J85 is located at one o'clock facing upstream and provides 300 mJ at a 2-Hz spark rate. The J85 is fueled by 12 dual-orifice, pressure-atomizing nozzles. They are assembled into single stage swirlers mounted uniformly around the dome. The flow characteristics of the nozzle are shown in Fig. 4.

Experimental Approach

In order to reproduce properly the results of Eq. (6)[4,12] for the J85, the corresponding range of τ_{sl} from 0.1 to 0.45 ms or $(\tau_{hc} + 0.021 \cdot \tau_{eb})$ from 0.025 to 0.25 ms is required (see Fig. 1). Because τ_{sl} depends primarily on the air inlet conditions for a given combustor and igniter [Eqs. (2) and (3)], it is clearly the ideal parameter to vary.

The manufacturer's ignition tests were conducted at combustor inlet pressures of 1.5, 1.0, and 0.4 atm and air and fuel temperatures from about 225 to 340 K, corresponding to

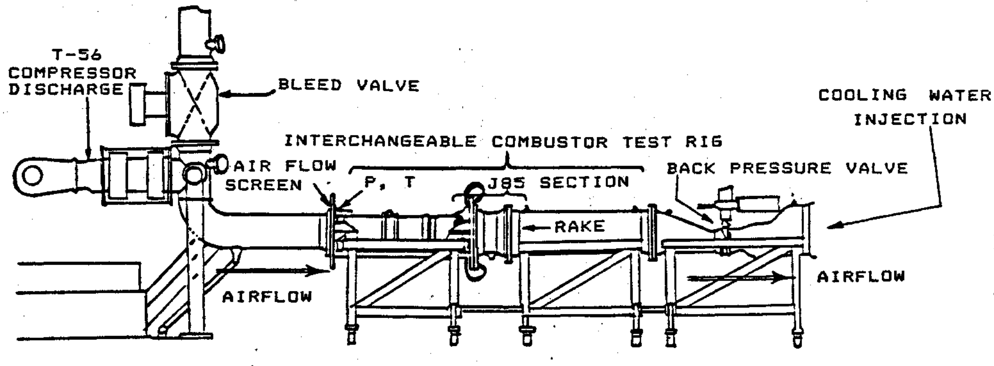

Fig. 2 NAPC Hot Gas Facility schematic, showing inlet instrumentation, J85 combustor, and exit plane thermocouple rake locations, and position of cooling water injection.

the cold-start and altitude-relight conditions of interest in the engine.[3] Over the duration of testing at NAPC, the (ambient) fuel temperatures encountered varied from 274 to 310 K. Further, the air inlet temperature was fixed at the T56 compressor discharge temperature, and the available combustor pressure range was 2–7 atm. Thus, the GE inlet conditions could not be attained in the Hot Gas Facility, which dictated that τ_{sl} be the scaling parameter for the tests in Trenton. Note that the air density term that appears in Eq. (3) makes τ_{sl} scaling different from V_{ref} scaling.

By selecting appropriate combinations of airflow and pressure at the fixed inlet air temperature, the range of τ_{sl} from 0.05 to 0.30 ms was achieved at NAPC. The nominal values actually used are shown in Table 2 and contrasted with those of General Electric.[3] The different range of fuel temperatures was accounted for in the data-reduction procedure predominantly via the fuel viscosity, which strongly affects the Sauter mean diameter in Eq. (4), as will be discussed below. The upper limit of 0.30 ms could not be extended because of large fluctuations in airflow and pressure at the low operating conditions. As shown in Table 2, the inlet conditions were chosen such that a small increment of 0.025 ms in τ_{sl} was obtained with each succeeding point. This procedure was selected to step piecewise up the curve shown in Fig. 1.

NAPC had eight fuels available for the J85 tests. In order to minimize expense and testing time, fuels estimated to perform similarly to those listed in Table 1 were eliminated. Evaporation times were calculated for all fuels under similar inlet conditions and grouped by high-, mid-, and low-range values. A home-heating oil and two diesel fuels with evaporation times comparable to the Table 1 fuels were thus not tested because these fuels were expected to perform similarly.

The ignition limits were measured by setting the inlet conditions of air pressure and airflow, firing the igniter, and slowly increasing the fuel flow in 2.5-kg/h increments at 30-s intervals. Ignition was achieved when all six of the rake exit plane thermocouples registered a sharp temperature increase. For the duration of the NAPC tests, the rake was positioned directly in line with the fuel injector at six o'clock. Altogether, nine operating conditions were tested and repeated at least once for each fuel.

The calculation of particular importance in the model is the Sauter mean diameter. In order to be consistent with previous work on the J85,[4,12,13] d_0 was calculated using Jasuja's[14] equation for a simplex pressure swirl atomizer. With the low fuel flows associated with the ignition limits, the nozzle operates only on the pilot, and the pressure swirl atomizer assumption is acceptable. For the J85, nozzle flows below 3.2 g/s signify pilot nozzle operation (see Fig. 4). The Sauter mean diameter is calculated as

$$d_0 = \frac{8.88\sigma^{0.6}\upsilon^{0.16}\dot{m}_f^{0.22}}{\Delta p^{0.43}} \mu\text{m} \tag{7}$$

where σ is the fuel surface tension in dyne/cm, υ the fuel viscosity in centiStokes (cS), $\dot{m}_f$ the fuel flow rate in kg/h, and Δp the nozzle pressure drop in atm.[14]

For all calculations, the spark-gap equivalence ratio ϕ in Eqs. (4) and (5) was assumed to be unity. This is consistent with the work of Peters and Mellor.[6] Stoichiometric adiabatic flame temperatures were calculated for Eqs. (3) and (5) using a constant pressure equilibrium flame temperature program.[15]

Table 1 Fuel property data

	JP-5	JP-7	SUNTECH A	SUNTECH B	DFM 3[a]
Hydrogen, wt %	13.7	14.5	12.2	12.9	13.4
Net heat of combustion, MJ/kg	42.91	43.44	42.08	42.40	42.57
50% boiling point, K	489.0	488.0	514.0	513.0	549.0
Density @ 294.3 K, kg/m^3	821.0	801.0	863.0	843.0	848.0
Viscosity @ 294.3 K, cS[b]	2.23	2.18	2.89	2.62	5.16
Surface tension @ 294.3 K, mN/m	23.80	26.01	26.98	26.79	26.96

[a]DFM means diesel fuel marine. [b]CentiStokes.

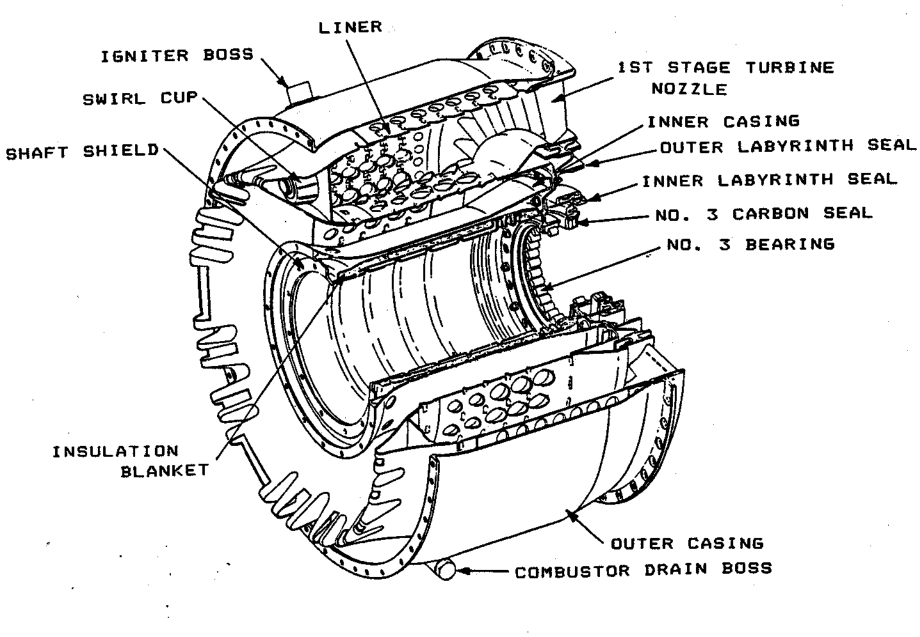

Fig. 3 J85 annular combustor schematic.

Table 2 Comparison of inlet conditions for τ_{sl}

τ_{sl}	GE[3]			NAPC		
Eq. (2), ms	$\dot{m}_a$, kg/s	P_{in}, atm	T_{in}, K	$\dot{m}_a$, kg/s	P_{in}, atm	T_{in}, K
0.050		—		13.5	5.0	530
0.100[a]	4.9	1.45	333	6.8	5.0	530
0.125		—		5.4	5.0	530
0.150[a]	1.5	0.40	306	4.5	5.0	530
0.175		—		3.9	5.0	530
0.200		—		3.7	4.0	530
0.225		—		3.3	4.0	530
0.250		—		1.6	2.0	530
0.300		—		1.4	2.0	530
0.370[b]	1.33	1.0	272		—	
0.450[b]	1.35	1.0	223		—	

[a]GE altitude relight. [b]GE cold start.

Results and Discussion

The final correlation of the 164 NAPC J85 data resulted in

$$\tau_{sl} = 1.55(\tau_{hc} + 0.021 \cdot \tau_{eb}) + 0.073 \tag{8}$$

with $r = 0.90$ and standard deviation $\sigma_y = 0.033$. When these data are correlated with the previous GE data,[3] a master correlation of $r = 0.90$, $\sigma_y = 0.042$, and

$$\tau_{sl} = 1.67(\tau_{hc} + 0.021 \cdot \tau_{eb}) + 0.064 \tag{9}$$

results. These data are depicted in Fig. 5. As desired, over the range of accessible τ_{sl}, the NAPC data have fallen between the groups of GE data and exhibit considerably less scatter. However, the fuels available at NAPC for these tests (Table 1) displayed a 47% narrower variation in viscosity at standard temperature, which may explain the decrease in data scatter.

The slope of the NAPC data in Eq. (8) differs from that of the GE data in Eq. (6). The lower NAPC slope is due to the concave curvature shown by the widely scattered NAPC data with τ_{sl} greater than 0.25 ms in Fig. 5. This data scatter is attributed to the low airflow conditions (nominally 1.6 kg/s) necessary to achieve the largest mixing times at the lowest air pressures. At these conditions, the fuel flow is also erratic and difficult to control.

For the reasons discussed, lower-range fuel flow meters were installed at NAPC for a portion of the ignition tests with JP-5. However, no significant decrease in data scatter was observed. The fuel flows steadied, but the erratic behavior of the airflow continued. Engine manufacturer's data in the upper right-hand corner of Figs. 1 and 5 may reflect similar problems at these rig operating conditions.

To determine the effects of the slope discrepancy in Eqs. (6) and (8) on the model's predictive capabilities, two J85 altitude-relight conditions[3] were examined. The combustor inlet conditions for these points are given in Table 3. For each set of conditions, Eq. (1) was reduced to a function of combustor inlet pressure, fuel viscosity, and slope m. The

Table 3 J85-21 engine combustor altitude-relight operating conditions[3]

	Point 1	Point 2
Engine operating condition (Mach no./alt, km)	0.5/7.62	0.6/7.62
Combustor airflow, kg/s	1.02	1.30
Combustor inlet total pressure, atm	0.405	0.434
Combustor inlet total temperature, K	250	225
Combustor fuel flow, g/s of JP-4	23.9	23.9

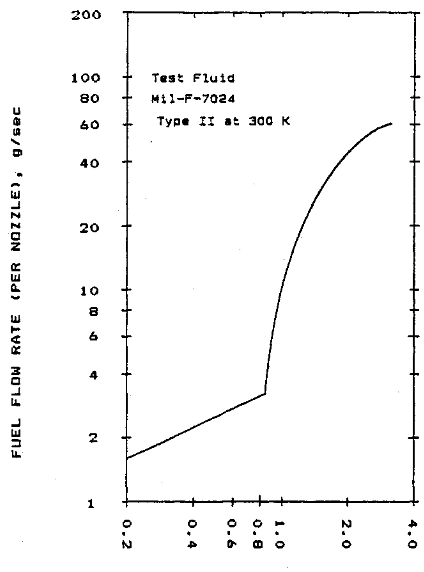

Fig. 4 Fuel nozzle flow characteristics.[3]

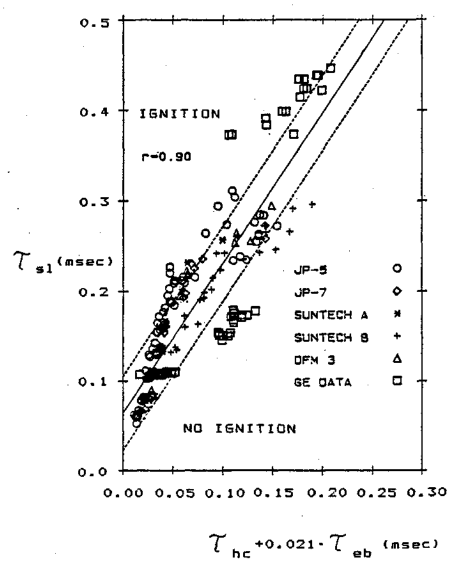

Fig. 5 Characteristic time model correlation of NAPC and manufacturer's J85 ignition data. Equation of the best-fit line: $\tau_{sl} = 1.67(\tau_{hc} + 0.021 \cdot \tau_{eb}) + 0.064$; $\sigma_y = 0.042$; 206 data.

Table 4 Predicted altitude-relight loss with high-viscosity fuel

Condition	Fuel, viscosity, cS at 311 K	p_{comb}, atm, actual at lightoff	m	p_{comb}, atm, calculated at lightoff	Δp_{comb}, %, due to $\Delta \nu$ fuel	Alt, km
$M = 0.5$	JP-4, @ 0.85 cS	0.405	1.55	0.390	—	7.62
			1.60	0.405	—	
			2.00	0.530	—	
	Alternative fuel, @ 1.8 cS	—	1.55	0.525	35	5.49
			2.00	0.735	39	5.27
$M = 0.6$	JP-4, @ 0.85 cS	0.434	1.54	0.434	—	7.62
			1.55	0.437	—	
			2.00	0.595	—	
	Alternative fuel, @ 1.8 cS	—	1.55	0.604	38	5.29
			2.00	0.846	42	5.09

resulting equations are as follows: for point 1,

$$0.5264 \cdot p_{comb}{}^{1.67} = 0.0121 \cdot m + 0.1245 \cdot m \cdot p_{comb} \cdot \nu^{0.224} \quad (10)$$

and for point 2,

$$0.4049 \cdot p_{comb}{}^{1.67} = 0.0121 \cdot m + 0.1046 \cdot m \cdot p_{comb} \cdot \nu^{0.224} \quad (11)$$

For point 1, the predicted combustor inlet pressures for relight corresponding to slopes of 1.55 and 2.00 were 0.39 and 0.53 atm, respectively (see Table 4). The slope corresponding to the actual inlet pressure of 0.405 atm was 1.60. The fuel used for this calculation was JP-4, with a viscosity of 0.85 cS at 311 K.

The same slopes of 1.55 and 2.00 were used to determine the percent increase in combustor inlet pressure for the J85 burning a higher-viscosity alternative fuel (1.8 cS at 311 K) with the same heating value under the same windmilling conditions. Both slopes showed nearly the same percent increases (35 and 39%) in inlet pressure. This was also evident with the point 2 analysis (see Table 4), where the percent increases were 38 and 42%.

More important than combustor pressure for ignition is the altitude required to relight the engine. Since compressor windmilling characteristics are not available for the J85, a procedure recommended by Tingle[16] was employed. The pressure ratio

$$\frac{p_{comb} - p_{static}}{p_{comp} - p_{static}} \quad (12)$$

where p_{comp} is the total compressor inlet pressure and p_{static} is the static atmospheric pressure at altitude,[17] was taken constant to determine the new static pressure and altitude for the higher-viscosity fuel.

The resulting relight altitudes predicted for the more viscous fuel are shown as the last column in Table 4. For the 0.5 Mach number operating condition, a loss of 2.24 ± 0.11 km in relight altitude is predicted by the model, while at 0.6 Mach number, the predicted loss is 2.43 ± 0.10 km. These results show that losses in altitude performance with a more viscous fuel are not dependent on the model equation's slope and can be obtained if other altitude-relight data are available.

Conclusions

Alternative-fuels ignition data from the J85 annular combustor tests at the Naval Air Propulsion Center were correlated successfully using a relatively simple model. Inlet airflows and pressures to the combustor were varied in small increments over a wide range of operating conditions. The use of the characteristic mixing time τ_{sl} as a scaling parameter for the inlet conditions was shown to assure the correspondence of the results to the GE cold-start and altitude-relight data shown in Fig. 1.

The slope of the ignition equation thus established is slightly lower than previous results for the J85.[4] Predictions in the relative loss in altitude-relight performance with increased fuel viscosity, however, show little sensitivity to the choice of slope in the ignition correlation. The correlation developed herein can thus be used to predict the ignition behavior of the J85 combustor over a wide range of fuels and conditions.

Acknowledgments

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