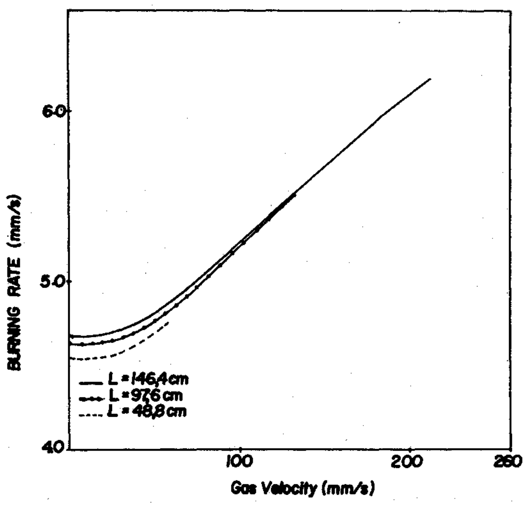

Fig. 5 Burning rate vs gas velocity data for various lengths of propellant.

The experimental method used to determine burning rate is accurate since previous experimental work[6] has not shown a temperature gradient across the propellant grain web. Thus, opening of burning detectors wires actually occurs only when the flame reaches each one, providing accurate results. Comparison of the experimental burning rate and predicted results from the design procedure, listed in Table 2, shows good agreement.

The analysis of the experimental results of rocket motors of several lengths indicates a small erosive burning effect. That is reasonable because the port-to-throat area ratio was high enough ($A_P/A_t < 2$) although the gas velocity reaches values greater than 180 m/s (threshold velocity[7,8]).

It can also be seen that erosive burning causes a decrease in *Isp*, C_F, and C^* and an increase in the burning rates along the propellant grain length. It should be pointed out that in the designs tested here the erosive burning was relatively small, and it was possible to verify a quite small influence on the rocket motors parameters.

In this work the erosive burning effects obtained were small. Therefore, further work will be done in a regime where strong erosive conditions are likely to occur.

Acknowledgments

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Characteristic Times for Lean Blowoff in Turbine Combustors

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Introduction

IGNITION and blowoff within turbine combustors have been studied extensively in the last few years; correlations for these processes have been made with characteristic time models. A lean blowoff model developed by Plee and Mellor[1] uses fuel properties, combustor inlet conditions, and combustor geometries to define characteristic times that are combined to represent a limit for blowoff. The model was originally developed for simple geometries and later applied to can combustors.[2] More recently, the model has been extended to annular combustors—specifically the General Electric (GE) J85.[3] As shown by Jarymowycz and Mellor,[3] the slow evaporation of fuel altered the correlation technique from that used previously for can combustors.[2] However, this conclusion was based on limited GE blowoff data taken by Oller et al.[4]

The purpose of this Note is to utilize a more complete set of new J85 lean blowoff data obtained at the Naval Air Propulsion Center (NAPC) and thus continue the validation of the model's application to annular combustors. In addition, because the NAPC facility could not reproduce the combustor inlet conditions used in the GE tests, the model was used to scale the combustor conditions at NAPC. A blowoff limit equation recommended here correlating data for two can combustors as well as the GE and NAPC J85 data suggests that the model is able to characterize blowoff independently of combustor type and can be used to scale test conditions.

Background

The lean blowoff model defined by Plee and Mellor[1] uses three characteristic times to represent blowoff: a droplet evaporation time (τ_{eb}), a fuel ignition delay time (τ_{hc}), and a shear layer residence time (τ_{sl}). At the limit for lean blowoff, the residence time in the shear layer will equal approximately the sum of the droplet evaporation time and ignition delay time:

$$\tau_{sl} \sim \tau_{hc} + k \cdot \tau_{eb} \tag{1}$$

with k a constant weighting factor found by Plee to be 0.011 for a best-fit straight line.[5] Since the equations for the

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calculations of the three times have been represented elsewhere (see Ref. 3), only a brief explanation of each follows.

τ_{eb} was evaluated with the d^2 law of Godsave,[6] which requires the Sauter mean diameter (SMD) of a fuel droplet. As before,[3] SMD (d_0) was evaluated with Jasuja's equation for a simplex pressure atomizing nozzle:

$$d_0 = (8.88)(\sigma_f^{0.6})(\nu_f^{0.16})(\dot{m}_f^{0.22})(\Delta p^{-0.43}) \quad (2)$$

where d_0 is in μm, σ_f is the surface tension (dynes/cm), ν_f is the fuel viscosity (cS), $\dot{m}_f$ is the fuel flow rate (kg/h), and Δp is the pressure drop across the fuel nozzle (atm). The ignition delay time is defined as the inverse of the hydrocarbon reaction rate.[5] The shear layer residence time represents the lifetime of a turbulent eddy and is derived from the reference velocity and the CO quench length (ℓ_q) defined by Mellor[8] in terms of the combustor diameter and the distance from the fuel injector tip to the centerline of primary or secondary air addition holes. For the annular J85, the annulus height (d_{comb}) replaces the combustor diameter[3]; one goal of the present work is to clarify at what engine power level the axial length shift from primary (ℓ_{pri}) to secondary (ℓ_{sec}) jets occurs.[8]

$$\ell_q^{-1} = (\ell_{pri\ or\ sec}^{-1} + d_{comb}^{-1}) \quad (3)$$

Lengths ℓ_{pri} and ℓ_{sec} are shown on the combustor cross section through a fuel injector in Fig. 1.

The characteristic times discussed include all the important variables of combustion: combustor geometry, fuel properties, and combustor inlet conditions. The three times are combined into one equation [Eq. (1)] that describes the conditions necessary for combustion to be maintained. Reference 1 provides an in-depth discussion of lean blowoff model formulation.

Experimental Approach

The blowoff data taken by Oller et al.[4] at GE were limited in the aspect that four power conditions were tested. A plot of these data correlated by the model exhibits clusters associated with the power conditions (see Fig. 2).[3] The equation obtained for the lean blowoff limit was

$$\tau_{sl} = 1.33[\tau_{hc} + (0.011)\tau_{eb}] + 0.25 \quad (4)$$

for 27 data with the correlation coefficient $r = 0.874$ and a standard deviation of $\sigma_y = 0.61$.[3] The 0.011 factor in front of τ_{eb} is held constant in all subsequent correlations to prevent the introduction of another variable and allow quick comparisons with previous correlations. The least-squares-fit line shown in the graph is the lean blowoff limit. The area to the left of the limit is the stable region, but the area to the right is unstable—here shear layer residence times are not long enought to allow a fuel droplet to evaporate and ignite. In order to substantiate the model further, it was desired to reproduce insofar as possible[9] the GE results and provide data between their tested power conditions. The program at NAPC was also designed to elucidate the effects of slow evaporation.

Blowoff testing was conducted with a J85-21 combustor at the Hot Gas Facility (HGF) at NAPC (the combustor is shown in Fig. 3); the facility has been described elsewhere.[9] Five fuels were selected for testing based on the ranges of evaporation times they would provide.[9] Suntech A and B are blends of fuels obtained from a local company and were chosen because of their intermediate range of evaporation coefficients. A breakdown of fuel properties is given in Table 1. The test matrix was developed using facility inlet conditions to obtain predetermined values of τ_{sl}.[9] Inlet air flows and pressures were calculated to step τ_{sl} from 0.80 to 3.25 ms in increments of 0.30 ms. A comparison of HGF and GE test points in Table 2 shows how the present test matrix includes a more continuous set of shear layer residence times.

Jarymowycz and Mellor showed that a shift from primary to secondary quenching lengths [see Eq. (3)] should be based on the evaporation time of the fuel.[3] The underlying assumption was that in older combustors with rich primary zones, larger droplets would take longer to evaporate and thus penetrate further into the primary zone. Evaporation

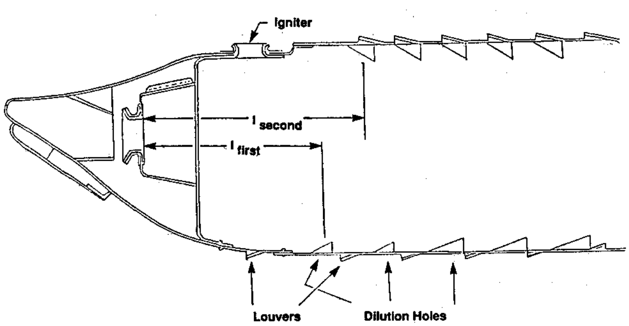

Fig. 1 J85 combustor cross section.

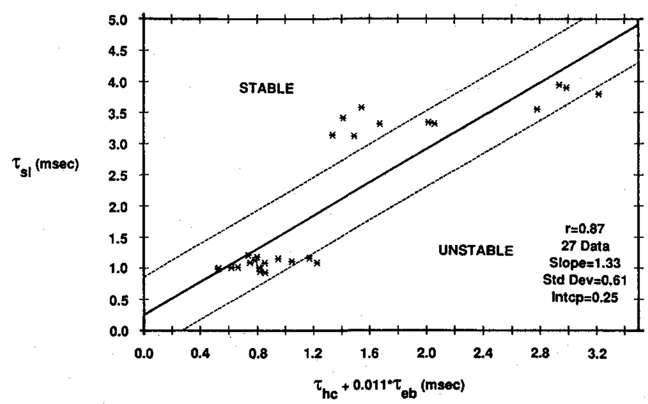

Fig. 2 Correlation of General Electric lean blowoff data (from Ref. 3).

Table 1 Fuel properties[9]

	JP-5	JP-7	Suntech A	Suntech B	DFM 3
Hydrogen (weight %)	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	488	514	513	549
Density at 294.3 K, kg/m^3	821	801	863	843	848
Viscosity at 294. 3 K, cS	2.23	2.18	2.89	2.62	5.16
Surface tension at 294.3 K, mN/m	23.80	26.01	26.98	26.79	26.96

times were characterized by the τ_{eb}/τ_{sl} ratio; therefore, a need for a quench length shift could be determined by a specific value for this ratio. The GE data yielded a range of τ_{eb}/τ_{sl} ratios from 32–82 with a best correlation for a quench length shift for τ_{eb}/τ_{sl} greater than any value between 45 and 72.[3] Since the HGF test matrix was designed to provide a more complete range of test points, it was expected that an ideal shift value could be pinpointed. The value that produced the best correlation in Eq. (1) would then be selected as the appropriate shift value in Eq. (3).

Experimental Procedure

To achieve lean blowoff, the inlet air flow and pressure were set for the desired point. The fuel flow was increased as the igniter was fired until ignition was achieved. The fuel flow was then slowly decreased until blowoff occurred. Data acquisition was begun at this time. Blowoff was defined with six thermocouples located in the combustor exit plane between the inner and outer annulus. The thermocouples were attached to a rake assembly that could be rotated about the combustor centerline but throughout testing remained positioned behind a fuel nozzle. At blowoff these thermocouples registered a sudden temperature drop (the lower limit before the drop usually being between 615 and 630 K). When all six thermocouples experienced this characteristic decrease, the flame was considered extinguished; this definition is in accordance with the GE test procedure.[10] Temperatures were monitored via a computer display system that provided updated information every 2 s. Each matrix point was repeated at least once, and the entire matrix was repeated for each fuel.

Results

The final correlation for the 98 HGF data was

$$\tau_{sl} = 1.41\,[\tau_{hc} + (0.011)\tau_{eb}] + 0.36 \qquad (5)$$

with $r = 0.86$, $\sigma_y = 0.33$, and a shift from primary to secondary quenching length for τ_{eb}/τ_{sl} greater than 51.0 (Fig. 4). This shift value provided the best correlation coefficient; however, there was no significant change for a quench length shift for the characteristic time ratio between 46.0 and 56.0. The Sauter mean diameter correlation [Eq. (2)] is the largest source of uncertainty because it was not obtained for the J85 fuel injector, the fuels in Table 1, or the inlet conditions in Table 2. Since the fuel viscosity is a key term in SMD calculation, the 47% narrower variation in HGF fuel viscosities compared to GE fuel viscosities could be the reason for the decreased scatter in the HGF data ($\sigma_y = 0.33$) compared to the GE data ($\sigma_y = 0.61$).[9]

The GE and HGF data are quite comparable as shown by the combined correlation of

$$\tau_{sl} = 1.34\,[\tau_{hc} + (0.011)\tau_{eb}] + 0.39 \qquad (6)$$

for 125 data with $r = 0.86$, $\sigma_y = 0.41$, and a quenching length shift for τ_{eb}/τ_{sl} greater than 51.0 (Fig. 5). Again, no significant difference in the correlation coefficient was observed

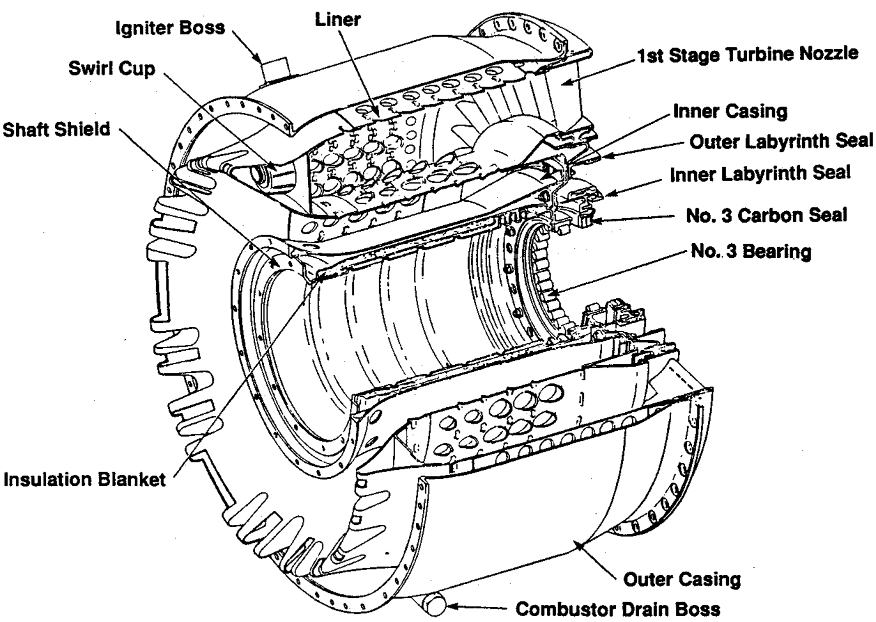

Fig. 3 J85 annular combustor (from Ref. 4).

Table 2 Comparison of GE and HGF τ_{sl} ranges

GE test points[4]				Hot Gas Facility test matrix			
Airflow, kg/s	Air pressure, atm	Inlet temp, K	τ_{sl}, ms	Airflow, kg/s	Air pressure, atm	Inlet temp, K	τ_{sl}, ms
1.50	0.40	306	0.96	12.47	5.10	530	0.83
4.90	1.45	333	1.04	10.01	5.10	530	1.04
				7.51	5.10	530	1.39
				6.01	5.10	530	1.73
				5.00	5.10	530	2.08
				3.65	4.08	530	2.28
				1.61	2.00	530	2.53
1.33	1.00	272	3.15	0.77[a]	1.09	530	3.27
1.35	1.00	223	3.20	0.68[a]	1.09	530	3.27

[a] Indicates points not actually obtainable at Hot Gas Facility.

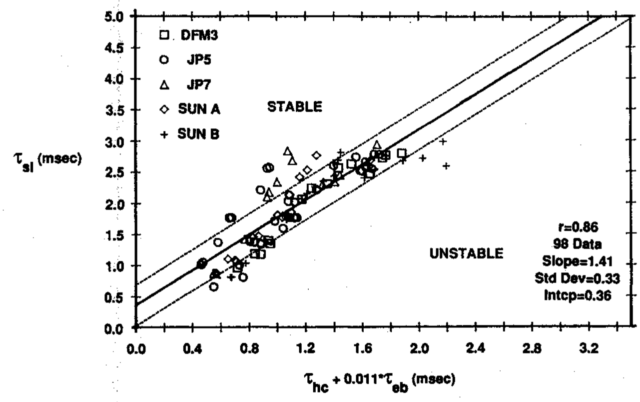

Fig. 4 Correlation of Hot Gas Facility lean blowoff data.

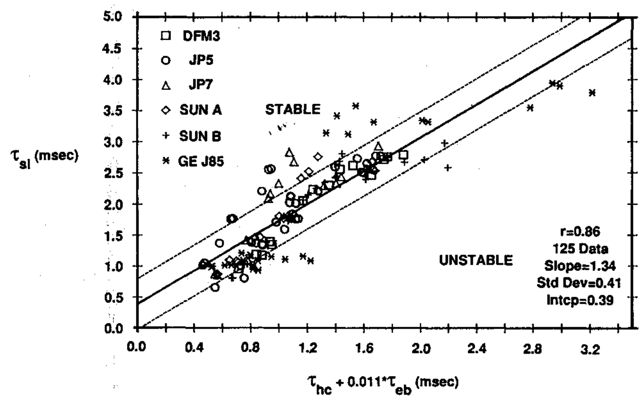

Fig. 5 Combined GE and HGF lean blowoff correlation.

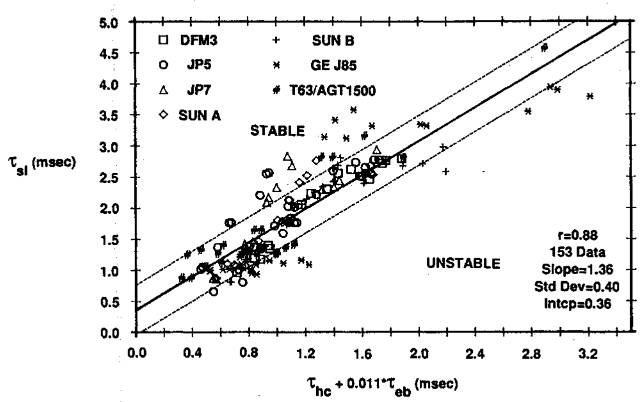

Fig. 6 Combined J85 (GE and HGF data), T63, and AGT-1500 lean blowoff correlation.

for a shift in the range of 46.0–56.0. The high degree of linearity in Eqs. (4–6) shows that the model applies well to the J85.

A combined can and annular combustor correlation performed with J85 (GE[3] and HGF), T63,[2] and AGT-1500[2] blowoff data resulted in a best-fit line of

$$\tau_{sl} = 1.36[\tau_{hc} + (0.011)\tau_{eb}] + 0.36 \tag{7}$$

for 153 data with $r = 0.88$ and $\sigma_y = 0.40$ (Fig. 6). In Ref. 3, the option of using the reference velocity instead of a constant velocity (50 m/s) in the Nusselt number calculation associated with the full evaporation coefficient β was explored. Since an improved correlation resulted, it was reasoned that the reference velocity is a better approximation of the relative droplet velocity than the constant velocity used previously. Reference velocities were thus used to reevaluate the evaporation times from Ref. 2 for T63 and AGT-15000 data both in Ref. 3 and in obtaining Eq. (7). Even though Eq. (7) represents a fit of 153 data rather than 55,[3] a quick comparison of Eqs. (4–7) shows little variation in slope or intercept despite the increased data base.

Conclusions

The high correlation coefficient obtained from the Hot Gas Facility data successfully confirmed the application of the lean blowoff model to the J85 annular combustor. Data from various fuels collapsed onto nearly the same line. Hot Gas Facility testing was designed to fill gaps in the GE results, which was accomplished by using τ_{sl} as a scaling parameter in the formation of the test matrix. The slope of the best-fit line agreed well with GE data within the same range. A sufficiently wide range of evaporation times was available to enable the choice of a suitable shift value in the length scale calculation. A shift in the quench length for $\tau_{eb}/\tau_{sl} > 50$ is recommended for the J85. With modern, lean-burning annular combustors and current atomization capabilities, this flame lengthening may not be an important consideration.

The Hot Gas Facility data also correlated well with AGT-1500 and T63 rig data, demonstrating the model's ability to characterize lean blowoff limits independently of combustor type. The recommended equation for the lean blowoff limit is Eq. (7). Equation (7) has been developed for standard and regenerative cycles, can and annular combustors, and fuels from gasoline to diesel fuel marine.

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