Correlation of Lean Blowoff in an Annular Combustor

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Introduction

FUEL effects on limits of lean blowoff and spark ignition and gas turbine engine emissions or combustor efficiency can be examined with characteristic time models. As these models continue to be validated for engines burning alternative fuels, their potential as interim design tools is demonstrated. Combustor geometry, inlet conditions, and fuel injector properties are also model parameters.

The lean blowoff model was developed by Plee and Mellor[1] for simple geometries and was extended to can-type combustors by Plee[2] and Leonard and Mellor.[3] This Note extends the model further to lean blowoff limits in the GE J85 annular combustor.

The spark ignition and lean blowoff data for the J85 were taken by Oller et al.[4] The ignition data have already been correlated by Naegeli et al.[5] The blowoff data examined here were taken at the same inlet conditions as the ignition data. The fuels, operating conditions, and blowoff equivalence ratios are listed in Table 1. The stoichiometric adiabatic flame temperatures $T_{\phi=1}$ were calculated at Southwest Research Institute using an in-house constant pressure equilibrium flame temperature program.

Characteristic Time Model

A semiempirical model for lean blowoff has been derived by Plee and Mellor[1] for data from three simple geometries and a variety of fuels. The model defines three characteristic times in the burning process of a recirculation-held, spray diffusion flame: the shear layer mixing or residence time τ_{sl}, which is evaluated in the shear layer adjacent to the flame holding recirculation zone; a fuel vapor ignition delay time τ_{hc}; and a droplet evaporation term τ_{eb}. Since the J85 employs a conventional diffusion flame combustor, these times are those recommended for the blowoff model.[1] The lean blowoff limit becomes

$$\left(\frac{T_{in}}{T_{\phi=1}}\right)\cdot\tau_{sl}\sim\tau_{hc}+k\cdot\tau_{eb} \tag{1}$$

That is, the residence or mixing time in the shear layer just equals the sum of fuel evaporation and fuel vapor ignition delay times at the limit. The temperature ratio accounts for the heat release by combustion in the shear layer. The weighting factor k of 0.011 was obtained by Plee[2] for the best fit to Eq. (1). This equation can be restated as

$$\tau_{sl}\sim\tau_{hc}{}'+0.011\cdot\tau_{eb}{}' \tag{2}$$

where the prime denotes inclusion of the temperature ratio.

The shear layer mixing time τ_{sl} denotes the lifetime of a turbulent eddy in the shear layer. This eddy decay time is related to a macroscopic characteristic dimension and velocity.[6]

$$\tau_{sl}\sim\frac{\ell_q}{V_{\text{ref}}} \tag{3}$$

For CO emissions, the quench length ℓ_q is related to the axial distance from the fuel injector tip to the centerline of the primary or secondary air addition jets and the combustor diameter.[7] This length is also relevant to the blowoff model[2,3]; thus ℓ_q is defined as

$$\ell_q{}^{-1}=\ell_{\text{pri, sec}}^{-1}+d_{\text{comb}}^{-1} \tag{4}$$

According to Leonard,[8] the shift of ℓ_{pri} to ℓ_s occurs when the primary zone equivalence ratio (ϕ_{pz}) exceeds unity. Previously, the blowoff model has correlated combustors with lean primary zones. This will be the first application of the model to a combustor with a rich primary zone at blowoff.

The ignition delay time τ_{hc} is derived for lean fuel and air mixtures.[1] It is defined as the inverse hydrocarbon reaction rate

$$\tau_{hc}=\frac{b\,\exp(E/RT_{\phi=1})}{\phi} \tag{5}$$

where b is the pre-exponential factor; E is the activation energy; and R is the universal gas constant.

The droplet evaporation term τ_{eb} is determined by fuel volatility and Sauter mean diameter (d_0). The J85 incorporates twelve dual orifice pressure atomizing nozzles. For the operating conditions described in Table 1, the nozzles operate only on the pilot, and Jasuja's[9] equation for a simplex pressure atomizing nozzle is used.

$$d_0=8.88\,\sigma_f^{0.6}\cdot\nu_f^{0.16}\cdot\dot{m}_f^{0.22}\cdot\Delta p^{-.43} \tag{6}$$

The Sauter mean diameter (μm) is dependent on the fuel surface tension σ_f (dyne/cm), viscosity ν_f (centiStokes), flow rate $\dot{m}_f$ (kg/h), and pressure drop across the nozzle Δp (atm).

The fuel evaporation time is evaluated from the "d²" law of Godsave[10]

$$\tau_{eb}=\frac{d_0^2}{\beta} \tag{7}$$

where β is the evaporation coefficient for forced convection.

Table 1 J85 lean blowoff data[4,5]

Fuel	T_{in},K	P, atm	$\dot{m}_a$, kg/s	ϕ	$T_{\phi=1}$, K
1C	272	1.00	1.328	.086	2275
	256	1.00	1.318	.086	2269
	240	1.00	1.318	.092	2263
	234	1.01	1.314	.112	2261
	229	1.01	1.356	.116	2259
13C	273	1.00	1.316	.229	2276
15C	223	1.00	1.353	.279	2253
	234	1.00	1.353	.245	2256
	242	1.00	1.345	.193	2258
	256	1.00	1.345	.180	2264
	269	1.04	1.339	.132	2269
2C	305	0.41	1.483	.163	2271
1C	335	1.46	4.814	.018	2305
	305	0.41	1.396	.076	2270
	307	0.37	1.553	.008	2268
13C	335	1.45	4.693	.045	2307
	305	0.43	1.398	.270	2272
15C	333	1.46	4.858	.030	2301
	306	0.42	1.621	.126	2267
9C	333	1.45	4.776	.047	2313
	309	0.42	1.390	.117	2280
	307	0.40	1.549	.105	2279
8C	335	1.46	4.724	.050	2318
	306	0.41	1.400	.114	2282
	306	0.38	1.578	.113	2280
14C	337	1.50	4.775	.068	2317
	308	0.41	1.417	.228	2280

[a] $\tau_{ed}/\tau_{sl}\geq 90$.

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Table 2 Fuel property data[4]

	Fuels						
	1C	2C	8C	9C	13C	14C	15C
Hydrogen, wt %	14.38	13.78	12.00	13.06	13.15	11.77	14.29
Fuel/air stoichiometry lb fuel/lb air	0.0676	0.0681	0.0700	0.0687	0.0690	0.0702	0.0680
Net heat of combustion, MJ/kg	43.48	43.11	42.11	42.81	42.62	41.86	43.27
50% boiling point, K	460	491	481	472	547	531	459
Density, @ 294.3 K kg/m^3	761.9	813.4	833.0	800.2	846.2	877.7	782.4
Viscosity, @ 294.3 K cStk	1.04	2.14	1.26	1.14	4.61	3.57	1.36
Surface tension, @ 294.3 K, mN/m	22.80	26.45	25.09	24.12	28.55	29.98	24.78

Correlation

The lean blowoff data involved seven different fuel blends. The various fuels and their properties are listed in Table 2.

Because the J85 is designed to burn rich in the primary zone, a low primary zone air mass flow fraction ($\dot{m}_{apz}/\dot{m}_a$) was selected to calculate the primary zone equivalence ratio which appears in τ_{hc}. Some sources[11,12] have used a ratio of 0.30, but this value did not correlate well (see Table 3). The value of 0.12 correlated better and was the value for dome flow suggested by GE.

Unlike can combustors, the annular J85 does not have a row of large primary air addition holes to fully quench the reactions; instead, several rows of smaller dilution holes are evident as shown in Fig. 1. Equation (4) must then be adjusted for the geometric differences of the J85. The logical assumption is to treat the first and second rows of air dilution holes as the first and second quenching locations, respectively. Thus, the axial distance from the fuel nozzle to the first and second dilution rows replaces the primary and secondary rows, respectively, in Eq. (4), and d_{comb} becomes the annulus height.

$$\ell^{-1} = \ell_{\text{first, second}}^{-1} + d_{\text{comb}}^{-1} \tag{8}$$

The criterion presented by Leonard[8] in shifting the ℓ_q calculated from first to second hole row at ϕ_{pz} greater than unity did not correlate favorably (see Table 3). Another criterion presented by Mellor and Washam[13] for an ℓ_q shift for the overall ϕ greater than 0.2 also did not show favorable results. Several other values of ϕ for the quench length shift were examined in order to find the best fit line, but none of the values increased the correlation coefficient r significantly.

At this point, the droplet evaporation term was examined. The correction of the evaporation coefficient for forced convection assumes a droplet relative velocity of 50 m/s. However, this is based upon the work of Plee and Mellor[1] for an experimental test rig. In a combustor, the reference air velocity V_{ref} is a closer approximation to the relative droplet velocity and it varies as inlet conditions to the combustor change. Table 3 shows an improvement in the correlation with this velocity correction; however, the results are not yet satisfactory ($r = 0.78$).

After examining a small group of data that did not correlate well, it was noticed that these datum points all had droplet diameters exceeding 130 μm. By shifting ℓ_q for d_0 greater than 130 μm, a much improved correlation resulted. This suggests that in older combustors with rich primary zones and coarse atomization at low power, large droplets penetrate to the end of the primary zone. Because the local stoichiometric eddies in the shear layer are the last to extinguish, the largest droplets govern the final length of the shear layer.

Table 3 Correlations using ℓ_q shift

Correlation ℓ_q shift	$\dot{m}_{apz}/\dot{m}_a$	Slope	y-intercept	Coefficient
none	0.30	1.52	0.62	0.64
none	0.20	1.73	0.49	0.70
none	0.12	1.86	0.43	0.74
$\phi_{pz} \geq 1.0$	0.12	1.85	0.07	0.69
$\phi_{\text{TOT}} \geq 0.15$	0.12	1.86	0.05	0.70
$\phi_{\text{TOT}} \geq 0.20$	0.12	1.86	0.01	0.71
$\phi_{\text{TOT}} \geq 0.25$	0.12	1.85	−0.01	0.73
$\phi_{\text{TOT}} \geq 0.30$	0.12	1.86	−0.03	0.74
$\phi_{pz} \geq 1.0^{a}$	0.12	1.21	0.38	0.78
$\phi_{\text{TOT}} \geq 0.15^{a}$	0.12	1.21	0.36	0.78
$\phi_{\text{TOT}} \geq 0.20^{a}$	0.12	1.21	0.34	0.80
$\phi_{\text{TOT}} \geq 0.25^{a}$	0.12	1.19	0.32	0.82
$\phi_{\text{TOT}} \geq 0.30^{a}$	0.12	1.19	0.30	0.83
$d_0 \geq 130\ \mu m^{a}$	0.12	1.34	0.16	0.87
$\tau_{eb}/\tau_{s1} \geq 33.0^{a}$	0.12	1.34	0.32	0.83
$\tau_{eb}/\tau_{s1} \geq 42.0^{a}$	0.12	1.33	0.32	0.83
$\tau_{eb}/\tau_{s1} \geq 45.0^{a}$	0.12	1.33	0.25	0.87
$\tau_{eb}/\tau_{s1} \geq 72.0^{a}$	0.12	1.32	0.24	0.87
$\tau_{eb}/\tau_{s1} \geq 73.0^{a}$	0.12	1.30	0.23	0.86
$\tau_{eb}/\tau_{s1} \geq 90.0^{a}$	0.12	1.20	0.31	0.83

[a]Corrected droplet relative velocity.

Realizing the importance of vaporization effects in predicting the quench length shift, the τ_{eb}/τ_{s1} ratio was examined. Previously this ratio was examined by Leonard[8] for vaporization effects in the efficiency model. By correlating the blowoff model with the ℓ_q shift at τ_{eb}/τ_{s1} greater than 45, the correlation coefficient reaches 0.874. Any shift of ℓ_q in which the low value of τ_{eb}/τ_{s1} is between 45 and 72 achieves this maximum correlation. Because this range of values is so wide, additional J85 data would be necessary to narrow these margins.

As droplet evaporation times increase, fuel penetration effects are also possible. The use of the fuel injection parameter τ_{fi} for simple flameholders as examined by Plee and Mellor[1] was attempted. When the τ_{fi}'/τ_{s1} ratio is greater than ten, fuel penetration effects are considered to be important.[1] However, the ratio of τ_{fi}'/τ_{s1} for the J85 did not consistently exceed this value.

The final correlation of twenty-seven J85 lean blowoff data shows

$$\tau_{s1} = 1.33(\tau_{hc}' + 0.011 \cdot \tau_{eb}') + 0.25 \tag{9}$$

with a value of $r = 0.874$ and standard deviation $\sigma_y = 0.61$.

The results of Leonard and Mellor[3] using AGT-1500[3] and T63[3] blowoff data showed

$$\tau_{s1} = 2.13(\tau_{hc}' + 0.011 \cdot \tau_{eb}') + 0.22 \tag{10}$$

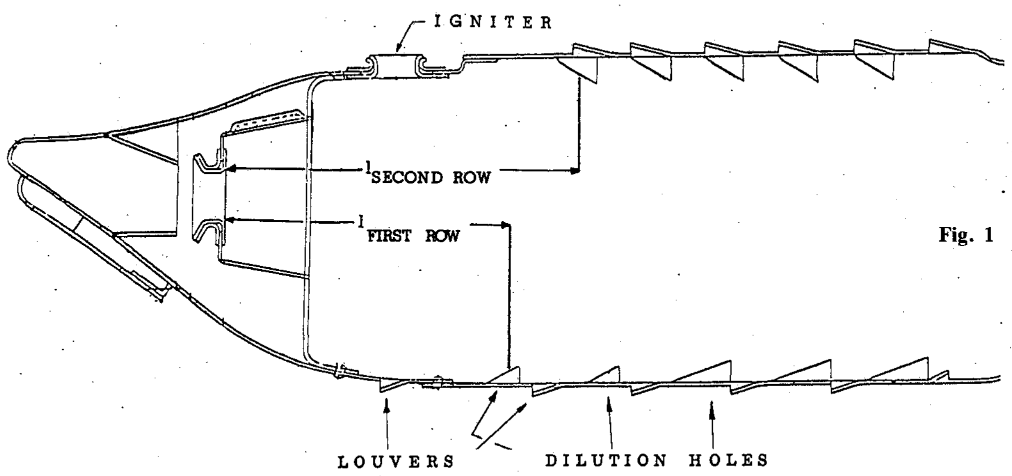

Fig. 1 J85 annular combustion schematic.

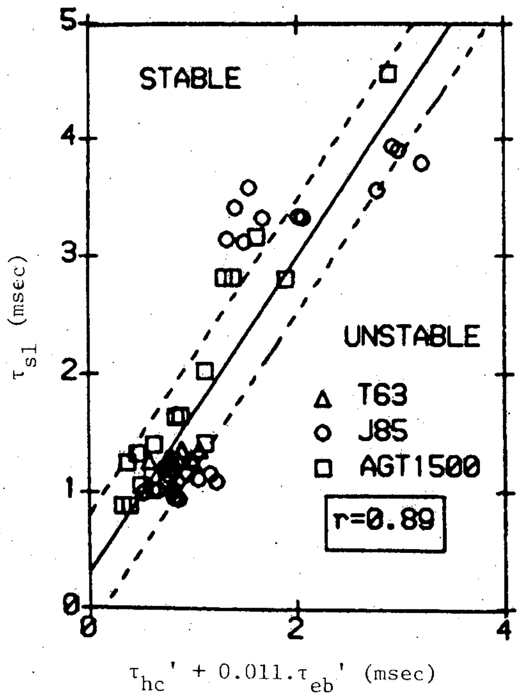

Fig. 2 Characteristic time model correlation of T63, AGT-1500 and J85 blowoff data. Equation of the best fit line: $\tau_{sl} = 1.34$ $(\tau_{hc}' + 0.011, \tau_{eb}') + 0.31$; $\sigma_y = 0.48$; 55 data.

with $r = 0.91$. The T63 and available AGT-1500 (DF-2 fuel only) data were again reproduced, but with the reference velocity correction. When these results are correlated with the J85 data

$$\tau_{sl} = 1.34(\tau_{hc}' + 0.011 \cdot \tau_{eb}') + 0.31 \tag{11}$$

with $r = 0.89$ and $\sigma_y = 0.48$. Equation (11) is preferred to Eq. (10) because of the reference velocity correction. The new results are depicted in Fig. 2. The region to the right of the correlated line represents extinction where fuel droplets cannot evaporate and ignite in time sufficient to sustain a stable flame. The area to the left is the stable region with the correlated line representing the limit of limit blowoff.

Conclusion

The extension of the blowoff model to an annular combustor was successful. Twenty-seven data were used to correlate the model. The droplet relative velocity used to calculate the evaporation term in an experiment test rig was corrected for use in a gas turbine engine. The vaporization effects associated with the poor atomization were accounted for by using a dimensionless ratio to predict a flame lengthening; however, more blowoff data on the J85-21 combustor are needed to establish the exact value of the ratio for which the flame length shift occurs. Finally, a single blowoff limit curve was developed for three engines.

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