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Fuel Property Effects on Radiation Intensities in a Gas Turbine Combustor

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The effect of fuel properties on primary zone radiation intensities in gas turbine combustors is examined. This study concludes that there is a strong empirical relationship between the primary zone radiation intensity and two fuel properties—percent hydrogen and percent polycyclic aromaticity. These two properties are combined in a single parameter called "effective hydrogen content," which is then used to correlate radiation intensities from seven different fuels burning under a variety of operating conditions. The explanation for the empirical relationship is that effective hydrogen content is a measure of the soot-forming tendency of a fuel.

I. Introduction

GAS turbine combustors have a distinct advantage over other types of powerplants: their ability to efficiently burn fuels whose properties vary over a considerable range. This tolerance for wide specification fuels has been the basis for a good deal of research into the effects of burning alternative fuels in gas turbine combustors. One applied aspect of this research has been an examination of the effect that fuel properties have on combustor soot and radiation. Of course, particulates are not only undesirable because they are a health hazard, but also because they make exhaust plumes visible. Furthermore, soot is thought to be the major source of gas turbine combustor radiation. High levels of flame radiation are objectionable because they can cause the combustor liner to operate at high temperatures, which leads to rapid fatigue and weakening of the liner structure.

In this empirical study, radiation intensities were measured in the fuel-rich primary zone of a model gas turbine combustor. Seven different fuels were burned by injecting fuel through a simplex pressure atomizing nozzle located in the center of a disk stabilizer for the flame. Windows along the sides of the combustor allowed radiation intensities to be measured at two different locations in the primary zone. These radiation intensities were then correlated with various fuel properties, and the two properties that most strongly influenced primary zone radiation were identified as fuel hydrogen and aromaticity (ring-bound carbon). These two properties were combined in a single parameter called "effective hydrogen content," and the correlation coefficients of radiation intensity vs effective hydrogen content were quite high for a variety of run conditions. The physical interpretation of this result is that fuels which are low in effective hydrogen content have a high propensity to form soot, which leads to high levels of flame radiation.

II. Literature Review

When the strong correlation between combustor pressure and flame radiation became apparent, studies on the nature of flame radiation and the influence of fuel properties were begun because the trend in engine development was toward engines of higher and higher compression ratios. Twenty years ago, one means of specifying the combustion cleanliness of a fuel was the fuel luminosity lamp rating. Basically, the relative soot-forming tendency of a fuel was measured by how much visible light it emitted while burning. Schalla and Hibbard[1] and Randall and Ritcheske[2] showed a correlation between fuel luminosity lamp ratings and combustor liner temperatures for various fuels. The assumption in that correlation was that convection heat transfer to and from the liner was the same for all fuels. Thus, any changes in combustor liner temperature with fuel type were attributed to the changes in flame radiation with fuel type.

The work of Schirmer et al.[3] undermined the confidence in the fuel luminosity lamp as a tool for predicting liner temperatures. These investigators made spectral measurements of luminous flame radiation, showing that it was composed mainly of blackbody rather than banded radiation. Since only 1% of the total flame radiation lay in the visible spectrum, Schirmer and his co-workers cautioned that fuel luminosity was not an accurate indicator of total flame radiation.

About the same time that Schirmer et al.[3] reported their spectral flame radiation measurements, Lefebvre and Herbert[4] published a paper containing a heat-transfer analysis of a combustor liner. Equations were given for convective and radiative transfer to and from the liner, and an empirical expression was developed for luminous flame emissivity:

$$\epsilon_f = 1 - \exp[-8.8\times 10^3 PL(r\ell)^{0.5} T_f^{-1.5}] \tag{1}$$

where P is the pressure (atm), L the luminosity factor, r the fuel/air weight ratio, ℓ the combustor mean beam length (m), and T_f the flame temperature (K). These investigators defined the luminosity factor

$$L = 7.53\ (\mathrm{C/H} - 5.5)^{0.84} \tag{2}$$

where C/H is the fuel carbon/hydrogen weight ratio as a good fit to experimental values of L for fuels ranging from kerosene to tarmac. The overall accuracy of the Lefebvre and Herbert heat-transfer analysis was established by agreement between liner temperature data and the analysis-based predicted liner temperatures. A footnote to their analysis is the fact that the calculation of the luminous flame emissivity using Eq. (1) requires a fairly accurate knowledge of burning conditions within the liner. In the variable r, the local average fuel/air ratio must be known, and to calculate T_f, one must know the local combustion efficiency as well as the local fuel/air ratio.

More than a decade later, Schirmer[5] reported the results of flame radiation studies in which fuel hydrogen content was varied between 14% and 15%. As suggested by the Lefebvre and Herbert[4] luminosity factor equation, a strong correlation between flame radiation and fuel hydrogen content was found. However, Schirmer found that the effect of fuel hydrogen on flame radiation decreased with increasing

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combustor pressure and increasing combustor exit temperature. The explanation for Schirmer's results presumably was that a lowering of hydrogen content increased both soot formation and flame radiation. However, in high-pressure, high-equivalence ratio flames where soot concentrations and emissivities were already high, an increase in soot formation had little effect on flame radiation. Thus, fuel hydrogen had less effect on flame radiation from high-pressure, high-equivalence ratio flames than on flame radiation from low-pressure, low-equivalence ratio flames.

During the past five years, numerous investigators[6-11] have reported the effects of fuel properties on liner temperatures for various combustor liners. Blazowski[6] successfully correlated liner temperatures for five different engines with fuel hydrogen content using a liner temperature parameter defined as

$$\Theta = \frac{T_l - T_{l,\text{base fuel}}}{T_{l,\text{base fuel}} - T_{\text{inlet}}} \tag{3}$$

where

T_l = liner temperature for test fuel

$T_{l,\text{base fuel}}$ = liner temperature for base fuel

T_{inlet} = inlet air temperature

Thus, this dimensionless liner temperature parameter represented the fractional increase (over the base fuel) in heat transfer to the combustor liner. Blazowski and Jackson[7,8] extended the early work with the liner temperature parameter, and found that it correlated excellently with fuel hydrogen in fuels whose hydrogen contents ranged between 10% and 16%.

Gleason et al.[10,11] studied the effect of fuel properties on liner temperatures for the J-79 and F-101 combustors. These investigators applied the liner temperature parameter of Ref. 8 and found that the liner temperatures of both engines correlated very well with fuel hydrogen content. However, the sensitivity of the two engine temperature parameters to fuel hydrogen was not the same. Specifically, the J-79 data fell on the same curve as the previous Blazowski and Jackson[7] correlation, but the F-101 data did not. Gleason et al.[11] argued that the relative leanness of the primary zone of the F-101 combustor made it less conducive to soot formation and therefore less sensitive to fuel hydrogen content. As for the effect of other fuel properties, Gleason et al.[10] noted that there was too much data scatter to judge whether fuel properties other than hydrogen were important in determining liner temperatures. However, radiation measurements made through the cross-fire tube indicated a trend for polycyclic aromatics to produce more radiation than monocyclic aromatics. Finally, they estimated the effect of fuel hydrogen content on combustor liner lifetimes.[10,11] They predicted that a drop in fuel hydrogen content from 14.5% to 12.0% would result in 50-60% reduction in liner life.

Another study of fuel property effects on liner temperatures was done by Vogel et al.[9] on a TF41 engine. Their conclusion was that the influence of multiring aromatic content on liner wall temperature was equal to and sometimes greater than the influence of hydrogen content.

In a very recent look at the liner temperature parameter correlations, Odgers[12] noted that the temperature parameter should not be used as an absolute measure of liner lifetime. He asserted that at idling conditions, a much larger range of the temperature parameter could be tolerated than at the full-load condition. Of course, his argument merely underscored the sensitivity of the temperature parameter to combustor inlet temperature.

Methods other than liner temperature parameter have also been used to study flame radiation. Naegeli and Moses[13] inserted a heat flux sensor in the primary zone wall of a T-63 combustor. Assuming convection to be the same for all fuels, changes in heat flux with fuel type were attributed to changes in radiation. Heat flux results for a wide range of petroleum fuels, water-emulsified fuels, and methanol-petroleum blends showed that H/C atom ratio was an excellent fitting parameter. Later, these same investigators[14,15] measured flame radiation through the primary zone air addition hole of the Phillips 2-in. combustor (see Schirmer et al.[3]). They clearly demonstrated that hydrogen content did not alone determine flame radiation.[15] Six fuels with nearly identical fuel hydrogen contents exhibited wide variations of flame radiation levels. Using average radiation fluxes for a large number of different run conditions, Naegeli and Moses[15] argued that flame radiation was linearly proportional to both hydrogen and polycyclic aromatic content. A detailed look at data in Ref. 15 revealed that there was considerable scatter in the correlations of radiation vs percent hydrogen and percent polycyclic aromatics for the individual run conditions. Moses and Naegeli[14] attributed such scatter to changes in flame length. Since they were able to measure flame radiation at only one axial position, it is now reasonable to believe that changes in flame length prevented them from always measuring peak flame radiation.

III. Experimental Apparatus

A. Combustion Tunnel and Test Combustor

The combustion tunnel shown schematically in Fig. 1 simulates conditions that are typical of present-day gas turbine combustion systems. Air for the combustor is supplied by a blowdown-type storage system, and the air is preheated without vitiation by a propane-fired indirect heater. Table 1 summarizes the capabilities of this combustion facility. Each of the parameters in Table 1 can be varied independently over the entire range of operating conditions. Details of a similar, but older, facility can be found in Refs. 16-18, while details of this facility can be located in Ref. 19.

Referring to Fig. 1, preheated air from the indirect heater enters the dump diffuser, then flows to the test combustor, where the test fuel is burned. Combustion gases are quenched with injected water at the exhaust plane of the test combustor before leaving the combustion tunnel through an elbow section and a back pressure valve. The elbow section is designed to divert most of the flow to the exhaust while simultaneously providing an opening for a sampling probe, to be depicted later.

A more detailed, cross-sectional view of the test combustor is shown in Fig. 2. Again, airflow is from left to right. Fuel is shown entering the combustor through a simplex, swirl atomizer located in the center of the disk flameholder. Two of the five pairs of windows along the sides of the combustor are also shown. Though combustion does not take place in an actual gas turbine combustor liner, this model does simulate a conventional diffusion flame burner in that it creates a fuel-rich, recirculation region near the fuel nozzle.

The advantage of the simplified flameholder geometry is twofold: the flowfield should be axisymmetric rather than three-dimensional, and the design allows physical and optical access to the combustor interior from the side (through the window holes). The inside diameter of the test combustor is 14.6 cm and the disk flameholder diameter is 11.4 cm.

Table 1 Operating limits of the gas turbine combustor

Inlet temperature	$273\ \text{K} \leq T_{\text{in}} \leq 950\ \text{K}$ (unvitiated)
Combustor pressure	$1\ \text{atm} \leq P \leq 12\ \text{atm}$
Air flow rate	$0.5\ \text{kg/s} \leq \dot{m}_a \leq 2.5\ \text{kg/s}$
Fuel flow rate	$0.15\ \ell/\text{min} \leq \dot{Q}_f \leq 2.1\ \ell/\text{min}$
Fuels	Propane, kerosene, diesel, gasoline, No. 6 oil

Table 2 Fuel property data[a]

Composition (weight %)	DF-2	Shale DFM	JP-10	No. 4	No. 6	Shale JP-5	UL gasoline
C	87.16	86.44	88.26	87.68	87.24	86.07	86.12
H	12.43	13.40	11.76	11.89	12.13	13.60	12.71
O	0.40	0.15	0.00	0.32	0.40	0.35	0.81
Molecular weight	191	193	274	167	211	190	325
Gross heat of combustion (mJ/kg)	44.51	46.60	44.92	44.74	44.49	45.99	45.43
Stoichiometric air/fuel ratio	14.31	14.52	14.15	14.18	14.23	14.58	14.43
Viscosity (cst at 40°C)	2.52	2.62	2.34	2.64	9.08	1.36	0.48
Specific gravity at 16°C	0.87	0.83	0.93	0.87	0.87	0.81	0.75
Aromaticity (weight percent)							
Monocyclic	12.9	12.0	0.04	12.8	5.8	13.6	42.2
Polycyclic	1.4	4.0	0.02	14.2	6.6	1.3	1.2
Total	14.3	16.0	0.06	27.0	12.4	14.9	43.4
Boiling point, °C							
10%	205	216	190	205	280	178	20
50%	273	274	192	257	338	212	107
90%	344	320	200	375	470	251	180

[a] Composition analyses by Galbraith Laboratories, Knoxville; distillation and physical data by U. S. Army Fuels and Lubricants Laboratory, San Antonio.

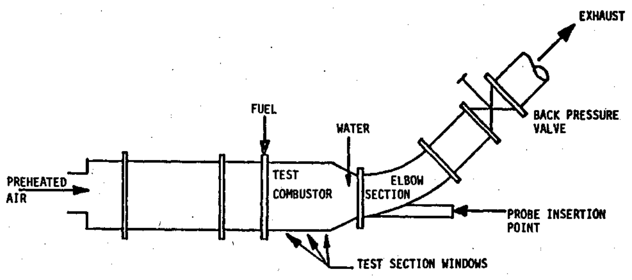

Fig. 1 Schematic of the combustion tunnel.

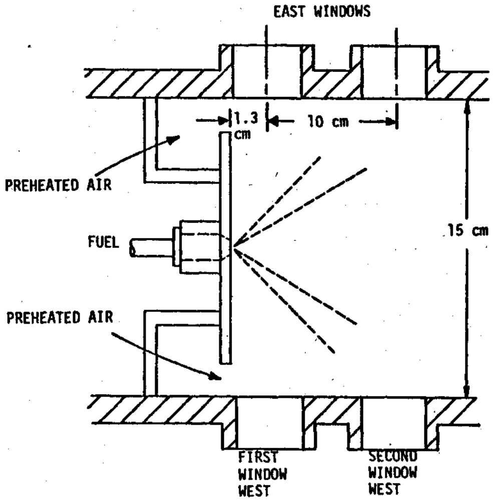

Fig. 2 Cross-sectional view of the test combustor.

B. Test Fuels

The test fuels in this experimental program are stored in drums, and a variable speed pump supplies fuel to the test combustor. Though the test combustor is capable of accommodating other types of atomizers, the test fuel is normally atomized by a Delavan simplex pressure atomizing nozzle which is mounted in the center of the circular disk flameholder. The nozzles used in the test combustor all provide a hollow cone spray with a 90 deg spray angle at atmospheric pressure. Fuel property data for the seven test fuels in this study are given in Table 2.

C. Radiometer

Flame radiation intensities are measured using a radiometer containing a coated thermopile which is designed to respond with equal sensitivity to all infrared radiation emitted by a flame over a wide range of temperatures. Optical components which determine the flame viewing angle and the spectrum of radiation transmitted to the thermopile are shown in Fig. 3. To record flame radiation intensity at different axial locations, the radiometer can be mounted in any of the five windows along the side of the combustor. The radiometer is calibrated with a blackbody whose maximum temperature is 1100°C. A cold, absorbing background is placed at the far wall, opposite the radiometer, to insure that no emission or reflection takes place there. Details of the background apparatus can be found in Ref. 18.

No attempt to separate band radiation from blackbody radiation was made because several sources (e.g., Lefebvre and Herbert[4]) conclude that band radiation is negligible in luminous flames such as those studied herein.

IV. Results and Discussion

Which radiation intensities should serve as an indicator of soot-forming tendency? Since soot formation takes place in the region near the fuel spray, it makes sense that the primary zone intensities are the best indicators of soot formation. An average of the radiation intensities from all five windows along the side of the combustor would not be as valid because it would reflect both soot formation (which depends mostly on fuel hydrogen and aromatic content) and soot oxidation (which depends on spray droplet size, spray penetration, temperature distribution, and oxygen concentration). As Gleason et al.[10] noted, peak liner temperatures are much more sensitive to fuel hydrogen content than average liner temperatures. Since radiation intensities peak in the primary zone, the use of primary zone radiation intensities as indicators of soot-forming tendency is sensible.

Finally, which primary zone radiation intensities should be used—first window, second window, or both? In this empirical study, the average intensity of the first two windows was used as an indicator of sooting tendency for two reasons.

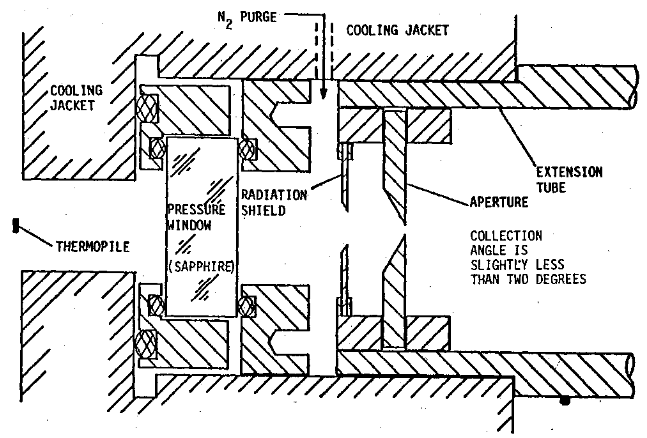

Fig. 3 Radiometer cross section.

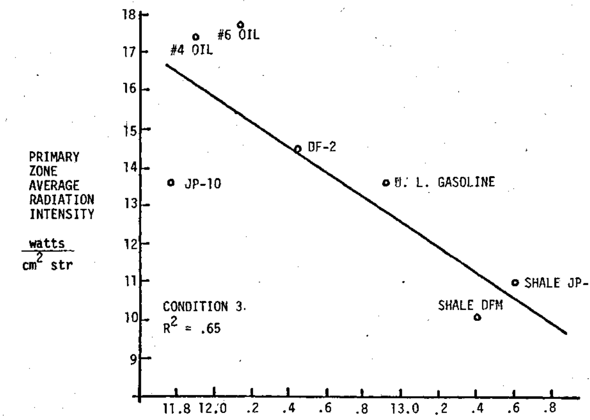

Fig. 4 Primary zone average radiation intensity vs hydrogen content (parameter 1).

First, as Moses and Naegeli[14] admitted, flame length greatly affected the radiation readings taken through the primary zone air addition hole of the Phillips 2-in. combustor. Thus, an average of two windows in the primary zone would help erase scatter due to slight changes in flame length with fuel type. Second, the use of an average radiation intensity for two windows would aid in removing scatter due to any small error in the radiation reading for any single window. Note that for all run conditions, radiation intensities were always highest in one of the first two windows.

Listed in Table 3 are the seven run conditions for which the primary zone radiation intensities were measured for several fuels. The fuel nozzle used for this empirical study was a Delavan 20-90 simplex pressure atomizer. The rating "20-90" means the hollow spray cone angle is 90 deg at 1 atm, and the nozzle will flow 20 gal/h of fuel at a nozzle differential pressure of 8.5 atm.

There are some problems with pumping two of the fuels used in this study. First, the No. 6 oil had the consistency of heavy grease at room temperature. Therefore, the No. 6 oil was heated to 40°C before pumping. The second problem was with unleaded gasoline. Because of its low viscosity, it could not be pumped at high flow rates or against high pressures. Thus, no unleaded gasoline data were obtained for conditions 4, 5, or 6.

Table 3 Fuel property study operating conditions

Condition	Pressure, atm	Inlet temperature, K	ϕ	Air mass flow, kg/s
1	3	700	0.25	1.0
2	3	700	0.15	1.0
3	3	700	0.20	1.0
4	3	700	0.30	1.0
5	6	700	0.25	1.0
6	12	700	0.25	1.0
7	3	600	0.25	1.0

Average primary zone intensities for all seven fuels burning under the run conditions in Table 3 are presented in Table 4. Primary zone effective emissivity was very close to 1.0 for all run conditions.

Since the fuel parameter most commonly used to correlate radiation intensities is weight percent hydrogen, the average primary zone intensities in Table 4 were correlated with hydrogen content using a least-squares fit. The results were only moderately satisfactory, which is indicated by the squares of the correlation coefficients, r^2, shown in Table 5. A typical correlation of average primary zone radiation intensity vs fuel hydrogen content is shown in Fig. 4.

The second parameter tried as a correlation of radiation intensities was an "effective hydrogen content," the form of which was first used by Naegeli and Moses[15]:

$$[\%\mathrm{H} - m(\%\mathrm{PA})] \qquad \text{(parameter 2)}$$

Naegeli and Moses reasoned that of two fuels with identical hydrogen contents, the fuel containing more polycyclic aromatics (PA) was more likely to form soot. Thus, the soot-forming tendency of a fuel depended on both hydrogen content and polycyclic aromatic content.

Parameter 2 was used by Naegeli and Moses[15] to correlate the radiation intensities for seven different fuels, averaged over a large number of different run conditions. In other words, Naegeli and Moses did not try to correlate the radiation intensities for each run condition; they reported only the correlation of parameter 2 with the average radiation intensity for each fuel over a number of run conditions. As with Naegeli and Moses, use of parameter 2 greatly improved the linearity of the present data, as can be seen from the values of r^2 in Table 6. Note that the multiplier, m, was optimized in each case.

Table 4 Average primary zone radiation intensities for seven fuels, W/cm^{2}str

Condition	No. 4 Oil	No. 6 Oil	DF-2	JP-10	UL gas	Shale DFM	Shale JP-5
1	16.1	15.8	14.2	13.5	13.5	10.5	10.0
2	18.7	17.3	13.1	13.1	14.1	10.3	9.9
3	17.4	17.7	14.5	13.6	13.6	10.1	11.0
4	17.4	15.5	13.6	12.9	[a]	10.4	9.5
5[b]	29.3	23.4	27.0	23.7	[a]	18.7	20.2
6[b]	34.5	22.4	32.5	30.5	[a]	28.7	27.7
7	11.0	9.8	9.7	9.7	9.9	7.9	6.3

[a] No gasoline data for this operating condition. [b] No. 6 oil datum for this run condition was not used in the correlations because the primary zone combustion efficiency at high pressure was apparently much lower for No. 6 oil than for the other six fuels.

Table 5 Flame radiation intensity correlation with fuel hydrogen

Condition	r^2	Standard deviation, %
1	0.77	9.5
2	0.61	17.2
3	0.65	14.3
4	0.70	14.1
5	0.63	13.0
6	0.63	6.3
7	0.85	5.6

Table 6 Flame radiation correlation with parameter 2

Condition	r^2	Standard deviation, %	m
1	0.85	8.7	0.055
2	0.86	11.5	0.130
3	0.78	12.7	0.083
4	0.94	7.3	0.120
5	0.74	13.3	0.074
6	0.82	5.3	0.110
7	0.92	4.9	0.051

Table 7 Flame radiation correlation with parameter 3

Condition	r^2	Standard deviation, %	n
1	0.93	5.8	0.15
2	0.92	8.5	0.24
3	0.87	9.6	0.19
4	0.99	3.4	0.22
5	0.82	11.2	0.17
6	0.92	3.6	0.21
7	0.94	4.1	0.11

Table 8 Flame radiation correlation with parameter 4

Condition	r^2	Standard deviation, %	n
1	0.97	3.8	0.13
2	0.91	9.2	0.17
3	0.87	10.0	0.14
4	0.99	3.1	0.18
5	0.92	7.1	0.18
6	0.99	1.3	0.19
7	0.94	3.8	0.11

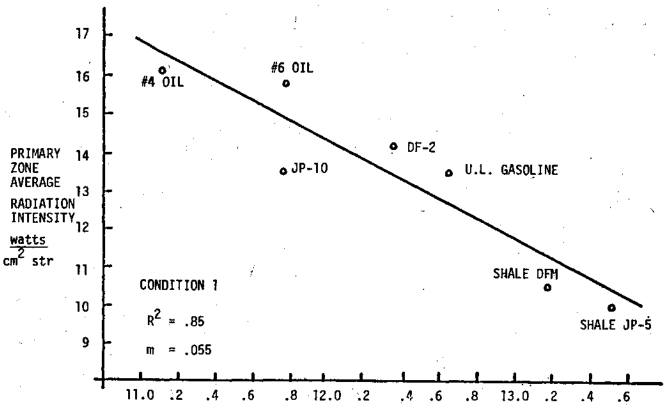

Fig. 5 Primary zone average radiation intensity vs effective hydrogen content (parameter 2).

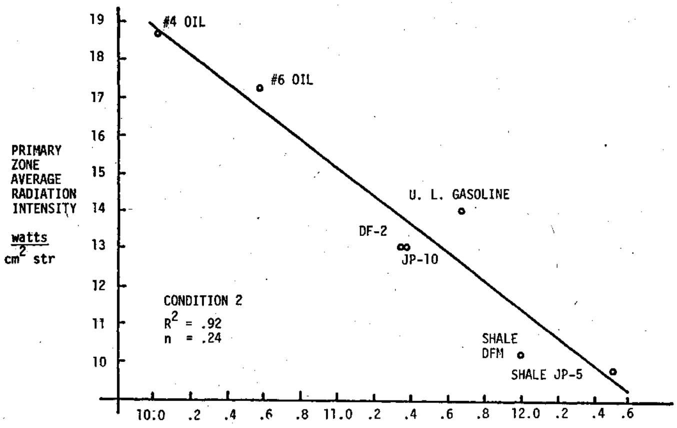

Fig. 6 Primary zone average radiation intensity vs effective hydrogen content (parameter 3).

For every run condition, the value of r^2 in Table 6 is larger than the value of r^2 in Table 5. A typical correlation of the primary zone average radiation intensity vs parameter 2 is shown in Fig. 5.

Another "effective hydrogen content" with a slightly different definition is:

$$[\%H - (\%PA)^n] \qquad \text{(parameter 3)}$$

The implication of parameter 3 is that the soot-forming tendency of a fuel is not linearly dependent on the polycyclic aromatic content. Parameter 3 was tried because it brought JP-10, a fuel with much less than 1% polycyclic aromatics, more into line with the other fuels. Compared with parameter 2, parameter 3 was a better correlating parameter for primary zone radiation intensity (see Table 7). Again, the exponent n was optimized in each case. One of the correlations of average primary zone radiation intensity vs parameter 3 is shown in Fig. 6.

Though parameter 3 is similar to parameter 2, the important difference between the two lies in how each parameter depends on the polycyclic aromatic (PA) term. Parameter 2 suggests that soot formation (therefore, primary zone radiation) increases linearly with PA; that is, an increase in PA should result in a proportional increase in soot formation. In contrast, parameter 3 infers that the first few percent of PA are far more important in the determination of primary zone radiation than the remaining polynuclear aromatics.

To illustrate this argument, consider two fuels, each with a hydrogen content of 13.0%. Fuel A has 10% PA, and fuel B has 20% PA. According to parameter 2, the effective hydrogen contents of fuels A and B are 12.0% and 11.0%, respectively. According to parameter 3, the effective hydrogen contents of fuels A and B are 11.4% and 11.2%, respectively. Parameter 2 would suggest that the soot-forming tendency of fuel B is considerably higher than that of fuel A. Parameter 3 would suggest that there is only a slight difference in the soot-forming tendency of the two fuels.

Finally, a third type of effective hydrogen content involving fuel hydrogen and total aromaticity (TA) was formulated and tried:

$$[\%H - (\%TA)^n] \qquad \text{(parameter 4)}$$

The results are given in Table 8.

As seen in the values of the correlation coefficient, r^2, parameter 4 fits the primary zone average radiation intensity data better than any of the other three parameters. Furthermore, the run conditions for which parameter 4 most

Table 9 Radiation indices from Fig. 1 of Naegeli and Moses[15]

Fuel no.	0	1	2	3	4	5	6
Condition							
A	1.0	1.49	1.37	1.85	1.88	1.48	1.66
B	1.0	1.22	1.11	1.57	1.57	1.19	1.45
C	1.0	1.49	1.50	1.88	1.77	1.49	1.30
D	1.0	1.16	1.14	1.20	1.25	1.18	1.24
E	1.0	1.28	1.28	1.56	1.54	1.27	1.47
F	1.0	1.13	1.15	1.33	1.34	1.12	1.30
G	1.0	1.28	1.24	1.48	1.47	1.32	1.41
H	1.0	1.19	1.19	1.26	1.33	1.19	1.31

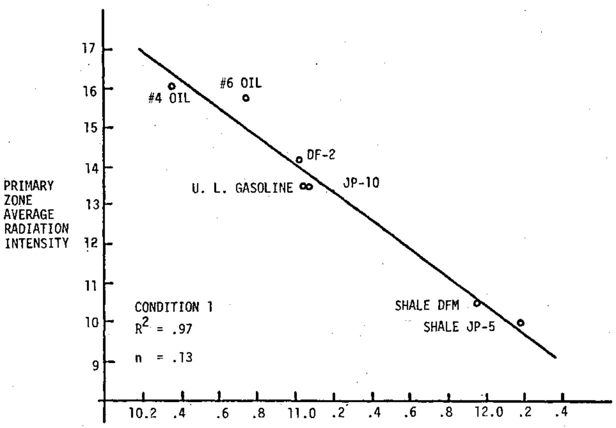

Fig. 7 Primary zone average radiation intensity vs effective hydrogen content (parameter 4).

Table 10 Correlation of Naegeli and Moses[15] **data with parameter 2**

Condition	r^2	Standard deviation, %	m
A	0.93	7.1	0.058
B	0.81	8.6	0.111
C	0.93	6.4	0.067
D	0.83	2.9	0.019
E	0.88	5.7	0.054
F	0.79	5.0	0.072
G	0.91	4.3	0.042
H	0.82	4.3	0.026

Table 11 Correlation of Naegeli and Moses[15] **data with parameter 3**

Condition	r^2	Standard deviation, %	n
A	0.94	6.4	0.276
B	0.83	8.6	0.404
C	0.92	7.1	0.302
D	0.85	2.9	0.128
E	0.89	5.7	0.263
F	0.79	5.0	0.316
G	0.92	4.3	0.220
H	0.83	4.3	0.154

Table 12 Correlation of TF41 maximum barrel temperatures at SLTO

Parameter	r^2	m	n
Hydrogen (#1)	0.40	—	—
Effective hydrogen (#2)	0.55	0.11	—
Effective hydrogen (#3)	0.56	—	0.35

improved the correlation coefficients were conditions 5 and 6, the high-pressure conditions. This improvement suggests that the conversion of single-ring aromatics to soot may be more prevalent at high pressure than at low pressure.

Note in Table 8 that the value of the TA exponent n equals 0.15 ± 0.04. In neither of the previous two tables does the value of n, nor the PA weighing factor m, show such a small variation (although the variation of n over the various correlations with parameter 3 is only slightly larger). A correlation of radiation intensity with parameter 4 is contained in Fig. 7.

Can parameter 3 be used to correlate radiation data from other investigators? Yes. For comparison, consider the data in Fig. 1 of Ref. 15. That figure gives relative radiation fluxes (dimensionless) for seven fuels under eight operating conditions. Those data are shown in Table 9. Application of parameter 2 to the data in Table 9 yields the results shown in Table 10. For comparison, the correlation of the Naegeli and Moses[15] data with parameter 3 is contained in Table 11.

With one small exception (condition C), the values of r^2 in Table 11 are greater than or equal to the corresponding values of r^2 in Table 10. Tables 11 and 7 indicate that parameter 3 is at least as good as, and probably better than, parameter 2 in correlating primary zone radiation intensities. If parameter 3 were indeed the more accurate correlating factor, then the statement in Ref. 15 that "polycyclic aromatics tend to be more effective in forming soot only when they are in very high concentrations" would be incorrect. In fact, the acceptance of "effective hydrogen content" as defined by parameter 3 would mean that the percentage of polycyclic aromatics converted to soot is highest for small concentrations of polycyclic aromatics. This suggestion that the efficiency with which polycyclic aromatics convert to soot decreases with increasing concentrations of polycyclic aromatics is similar to the widely observed trend regarding the conversion of fuel-bound nitrogen to NO_x (see Ref. 20). Summarizing, both parameters 2 and 3 predict a decrease in effective hydrogen content when the weight percentage of polycyclic aromatics in the fuel increases. However, parameter 3 differs from parameter 2 in that parameter 3 implies for a fuel containing 20% PA, the first 2% PA are more effective in reducing the effective hydrogen content than the remaining 18%.

Parameter 4 was applied to the Ref. 15 data without success. This failure indicates that the excellent results obtained from the application of parameter 4 to the primary zone average radiation intensities of the present study may have been fortuitous, meaning that the percentage of single-ring aromatics in any fuel may carry little weight in determining the sooting tendency of that fuel. An alternative interpretation is that there was too much scatter in the Naegeli and Moses data to reveal whether or not single-ring aromatics have a bearing on the effective hydrogen content of a fuel. Common sense would conclude that if multiring aromatics play a part in forming soot, then their smaller counterparts, single-ring aromatics, would play a similar role.

Does effective hydrogen content correlate liner temperature data? Yes. Vogel et al.[9] published maximum barrel wall temperatures for the TF41 engine at the sea level takeoff condition. These investigators measured liner temperatures for 12 fuels whose hydrogen contents varied between 11.9% and 14.4%, and whose PA contents ranged between 0.4% and 24.8%. Results of the attempts to correlate TF41 maximum barrel wall temperatures with either hydrogen or effective hydrogen content are presented in Table 12. Though none of the correlation coefficients are very high, effective hydrogen content as defined by either parameter 2 or 3 provides a fit to the barrel wall temperature data which is superior to the fit provided by hydrogen content alone. Data scatter, which plagues liner temperature data much more than it plagues radiation data, is responsible for the low correlation coefficients in Table 12.

Application of the effective hydrogen content to liner temperature data for modern engines is likely to be less successful than its application to older combustors, like the TF41 because the more recent combustors have more fuel lean primary zones, produce less smoke, and are therefore less sensitive to the fuel properties which promote soot formation. Gleason et al.[10] noted for the J-79 liner temperatures that there was too much scatter to judge whether fuel properties other than hydrogen were important in determining liner temperatures. Thus, correlation of liner temperature data with effective hydrogen content has not been attempted for engines other than the TF41 because there is little chance of substantially improving the quality of fit currently provided by actual hydrogen content.

To conclude this study of how fuel properties affect flame radiation, the following expression for the effective hydrogen content of a fuel

$$[\%\text{H} - (\%\text{PA})^n] \qquad \text{(parameter 3)}$$

where $0.1 \leq n \leq 0.4$ has been shown to be a very effective fitting parameter for the average primary zone radiation intensities of the present study and for the Naegeli and Moses[15] radiation fluxes. Furthermore, parameter 3 has been shown to provide a fairly good fit to the TF41 liner temperature data in Ref. 9. Though another expression involving total aromatics (parameter 4) was slightly more accurate in correlating the radiation intensities from the present study, this second expression could not be successfully applied to the Naegeli and Moses[15] fluxes.

V. Conclusions

Based on the experimental and analytical work reported herein, the conclusions for these gas turbine combustor soot and radiation studies are:

1) The fuel properties that most strongly affect primary zone radiation intensities are weight percentage hydrogen and weight percent aromaticity. Of these two properties, fuel hydrogen is the dominant parameter.

2) The present study indicates that primary zone radiation intensities correlate slightly better with total aromaticity (single and multiring aromatics) than with polycyclic aromaticity. However, application of the effective hydrogen content expression to the radiation intensities from another source results in two correlation coefficients, r^2, with the value of r^2 pertaining to the polycyclic aromatic expression being much higher than r^2 for the expression containing total aromaticity. Thus, whether or not single-ring aromatics enhance soot formation has not been proven.

3) The effect of polycyclic aromaticity on soot formation may be nonlinear. Though another source has asserted that the effect is linear, the present study has shown that an effective hydrogen content which has a nonlinear dependence on aromaticity is the best correlating parameter for primary zone radiation intensities from the present study as well as from the second source. The form of this effective hydrogen content parameter indicates that for a fuel containing high amounts of aromatics, the first one or two weight percent aromatics are far more important in determining soot-forming tendency than the remaining aromatics.

4) The enhancement of flame radiation by polycyclic aromatics can also be seen in maximum liner temperatures for at least one combustor, the TF41. However, the effect of polycyclic aromatics is not generally detectable in liner temperature data either because of scatter or because liner temperatures from many modern combustors exhibit little dependence on fuel properties.

5) One unanswered question from the study of primary zone soot formation is whether or not single-ring aromatics enhance soot formation. This study concludes that they do, but at least one other source surmises that they do not. A logical solution to this argument is to measure the primary zone radiation intensities from the combustion of several fuels containing little or no polycyclic aromatics and varying amounts of single-ring aromatics. Results from the present study indicate that the effect of single-ring aromatics is most pronounced at elevated pressures.

6) A second unanswered question regarding fuel property effects on primary zone radiation intensity is whether aromatics act linearly or nonlinearly to change the soot-forming tendency of a fuel. The fuel which has prompted the suggestion that the effect is nonlinear, JP-10, has very small amounts of aromatics; it would be useful to know whether other nearly pure fuels, such as isooctane or propane, yield results similar to the JP-10 data. Equally useful would be a test of two or more fuels having high aromatic levels. If the effect of aromatics is nonlinear, then the primary zone radiation intensities for two fuels, one having 25% polycyclic aromatics, the other 40% aromatics, will be about the same. If the effect is linear, then there will be a significant difference in the radiation intensities for the two fuels.

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