Influence of Fuel Composition on Flame Radiation in Gas Turbine Combustors

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Previous work on the correlation of flame radiation data from gas turbine combustors is reviewed. A study of the results obtained from the combustion of a wide variety of liquid hydrocarbon fuels in several different types of continuous-flow combustors shows that although hydrogen content provides a useful general indication of the influence of fuel composition on luminous flame radiation, a better fit to the measured values can be achieved by using the smoke point as the correlating parameter. The best representation of the experimental data is provided by the following two-property parameter that embodies both smoke point and naphthalene content: flame luminosity $= f[SP^{-0.92}(100 - N)^{-0.4}]$.

Nomenclature

C/H	= carbon/hydrogen ratio by mass
e_f	= flame emissivity
H	= fuel hydrogen content, percentage by mass
L	= luminosity factor
l	= beam length, m
N	= fuel naphthalene content, percentage by volume
P	= pressure, MPa
PA	= fuel polycyclic aromatic content, percentage by volume
q	= fuel/air ratio by mass
SP	= smoke point
T_f	= flame temperature, K

Introduction

IT is well known that in gas turbine combustion chambers a large proportion of the heat transferred to the liner walls is by radiation from the flame. In the primary combustion zone most of the radiation emanates from soot particles produced in fuel-rich regions of the flame. Soot may be generated in any part of the combustion zone where fuel/air ratios are locally high, but the main soot-forming region lies inside the fuel spray at the center of the liner. In this region local pockets of fuel and fuel vapor are enveloped in oxygen-deficient burned products at high temperature, thereby creating conditions that are highly conducive to soot formation.

At low pressures the presence of soot particles may give rise to a luminous flame, but usually they are too small in size to significantly affect the level of radiation.[1] However, at the high levels of pressure encountered in modern gas turbines, the soot particles attain sufficient size and concentration to radiate as blackbodies in the infrared region. It is under these conditions that radiant heating is most severe and poses serious problems in regard to liner durability.

Despite its considerable practical importance, the subject of flame radiation in gas turbine combustors has not been subjected to extensive experimental investigation. This is partly because of the formidable experimental difficulties involved, especially at high combustion pressures, but also because the designer has always been able to offset the heating effects of flame radiation by the injection of sizeable quantities of film-cooling air along the inner surface of the liner wall. On some engines this amounts to over one-third of the total combustor airflow.

The resurgence of interest in flame radiation in gas turbine combustors that occurred in the 1970s originated from the growing body of evidence on the performance penalties associated with film cooling, such as deteriorations in the temperature pattern factor and combustion efficiency at low power settings. It was also becoming increasingly recognized that film-cooling air is a main contributor to the presence of carbon monoxide and unburned hydrocarbons in the exhaust gases, especially at engine idling conditions. Designers are now fully aware of the paramount importance of reducing the amount of air employed in film cooling to an absolute minimum. The determination of this minimum quantity for any given combustor depends on a sound knowledge of flame radiation and the manner and extent to which flame radiation is affected by changes in combustor operating conditions, fuel type, and fuel-spray characteristics.

At the present time the main incentives for a better understanding of flame radiation in gas turbine combustors are the uncertainties surrounding the cost and availability of conventional fuel supplies, indicating the need for examination of the effects on flame radiation of possible changes in fuel properties. The most probable changes are expected to be a decrease in hydrogen content together with increases in aromatic compounds and fuel boiling range. Such changes are expected to promote the formation of soot, leading to an increase in engine exhaust smoke and, more importantly, increased radiative heat trasnfer from the flame to the liner. The impact of the latter is emphasized by the fact that small increases in liner wall temperature can seriously curtail liner life.[2]

A better understanding of radiative heat transfer is also needed to help establish realistic models for the production of heat-flux distributions within the combustion zone. Such analytical efforts could yield improved liner durability in future designs by prescribing optimum arrangements for the quantity and distribution of film-cooling air. This approach could also lead to significant reductions in the time and cost of liner development.

Received Sept. 1988; revision received Feb. 17, 1989.

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In recent years several reviews have been published on the subject of flame radiation.[3-5] The present work is confined to flame radiation in gas turbine combustors, with special emphasis on the influence of fuel composition on flame radiation. The work carried out to date in this area has led to few positive conclusions, mainly because much of the experimental evidence is confusing and sometimes contradictory. Most of the apparent anomalies, however, are due to the circumstance that flame radiation is dependent on a large number of parameters, none of which constitutes an independent variable. They include the size and geometry of the combustor, its operating conditions of pressure, temperature, velocity, and fuel/air ratio, and also various fuel factors such as chemical composition, mean drop size, drop-size distribution, and radial fuel distribution (effective spray cone angle). Nevertheless, it is fully established that flame radiation constitutes a significant proportion of the total heat transferred to the liner walls. It is comprised of nonluminous radiation, mainly from carbon dioxide and water vapor, which is fairly insensitive to fuel composition for the kerosene-type fuels employed in gas turbines, plus a luminous component that is very dependent on both the physical and chemical properties of the fuel.

Fuel Properties

Fuel properties can influence soot production in two ways; first by inducing the formation of local fuel-rich regions, and second by exerting variable resistance to carbon formation. The former is controlled by physical properties such as viscosity and volatility, which affect the mean drop size, penetration, and rate of evaporation of the fuel spray, whereas the latter relate to molecular structure. The extent to which fuel type affects flame radiation depends in any given situation on the efficiency of the processes whereby the carbon contained in the fuel is converted into soot.[6] The effect of fuel composition can be neglected when the quality of fuel air mixing is so good that the efficiency of carbon conversion to soot falls below 0.05%; at this point the nonluminous component of radiation becomes dominant. Also, if the conversion to soot exceeds 3%, the emissivity approaches so close to unity that variations in fuel composition have a negligible effect. For current combustor designs the efficiency of conversion to soot usually falls between these two extremes, so that fuel composition does have a significant effect on flame radiation and liner wall temperatures.

Most of the early studies on the influence of hydrocarbon type on sooting tendency concentrated on premixed or laminar diffusion flames[7-12] and hence cannot be related directly to the conditions prevailing within gas turbine combustors. Nevertheless, it is reasonable to assume that the trends observed will provide an indication of actual fuel performance. These studies show that the incipient sooting limit, i.e., the air/fuel ratio at which the flame first begins to produce soot, increases in the following manner: paraffins < olefins < dicycloparaffins < benzenes < naphthalenes.

Few basic studies have been carried out on the sooting tendencies of turbulent diffusion flames, but Wright's measurements on soot formation in a jet-stirred reactor[13,14] have relevance to gas turbine combustors because both systems employ backmixing of combustion products to stabilize the flame. As in previous studies, Wright found that soot forms at oxygen/carbon ratios greater than unity, but the strong recirculation of burned products did afford some broadening of the soot-free oxygen/carbon ratio.

The important influence of hydrogen content on flame radiation in gas turbine combustors was recognized in an early study by Lefebvre and Herbert.[15] These workers developed the following empirical expression for luminous flame emissivity:

$$e_f = l - \exp - [0.29PL(q\ell)^{0.5} T_f^{-1.5}] \tag{1}$$

where L is defined as

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

The overall accuracy of Eqs. (1) and (2) was established by agreement between measured liner wall temperatures and predicted values based on calculations of the heat flux to and from the liner walls utilizing Eqs. (1) and (2).

The important influence of hydrogen content on flame radiation was also demonstrated by Schirmer and his colleagues,[16,17] who investigated a wide range of fuels at combustion pressures up to 1.5 MPa (15 atm). The results of their tests on a Phillips 5-cm combustor showed a systematic increase in radiative flux with increase in combustion pressure and decrease in fuel hydrogen content. More recent work by Kuznar et al.[18] and Humenik et al.[19] on much larger gas turbine combustors has generally confirmed Schirmer's results.

Moses and Naegeli also used the Phillips 5-cm combustor, as well as a T-63 engine combustor, to study the effect of fuel consumption on flame radiation.[20] They concluded that the main factor influencing flame radiation is hydrogen content or C/H ratio. They also noted that fuel viscosity and boiling point distribution have no significant effect on radiation, even with endpoints as high as 675 K, which led them to conclude that the soot-forming reactions are gas-phase rather than liquid-phase pyrolysis. In a subsequent paper, Naegeli and Moses[21] confirmed the importance of hydrogen content, but they also presented evidence to suggest that fuel molecular structure can play a significant role in soot formation and flame radiation. In particular, it was found that a 20% naphthalene conduct could increase flame radiation by as much as 20% over predictions based solely on hydrogen content. Another interesting result from this study was that flame radiation correlated well with the fuel's smoke point despite strong differences in molecular structure.

By suitable blending, Dodge et al.[22] and Naegeli et al.[23] were able to produce fuels of constant hydrogen content and varying aromatic content. These blended fuels allowed them to study the separate effects on flame radiation of C/H ratio and percentage aromatics. They found that under some operating conditions the sooting tendency was affected significantly by polycyclic aromatics, but the C/H ratio remained as the principal correlating parameter.

Bowden and Pearson[24] used a model gas turbine combustor to examine the influence of fuel composition on several soot-related combustion phenomena. The combustion characteristics monitored were liner wall temperature, flame radiation, and exhaust smoke. Altogether, some 24 different test fuels were burned at combustion pressures up to 2.0 MPa (20 atm) with inlet air temperatures varying from 655 to 753 K. These conditions were chosen to simulate the takeoff and cruise regimes for a typical aerojet combustor.

The results obtained at all experimental conditions showed that hydrogen content and smoke point provided the best correlation with fuel combustion performance. Aromatic content, although adequate, was a poorer correlating parameter. It was observed that fuels containing high concentrations of naphthalenes, > 10% by volume, gave higher flame radiations than other fuels having the same hydrogen content. Bowden et al.[25] suggested that a combination of both hydrogen content and another property, e.g., smoke point or napthalene content, would provide a good overall measure of a fuel's soot-forming tendencies.

In a later study, Bowden et al.[26] measured the flame radiations produced by the combustion of seven different test fuels that had been previously selected to reflect the broadest spectrum of fuel properties to be found among practical kerosene fuels. These fuels were burned in three different combustors—a Rolls Royce Tyne combustor, a 5-cm Phillips combustor of the type that has beenused extensively in the United States for soot and radiation studies, and their own Shell-developed model combustor. All three combustors were oper-

Table 1 Fuel properties

Fuel type	Hydrogen content, % weight	Naphthalene content, % volume	Smoke point, mm	Total aromatics, % volume
JP 4	14.54	0.2	27	11.1
JP 4 Shale-derived	14.39	0	31	10.1
Blend 5	13.44	2.8	16	20.1
Blend 6	12.94	3.8	12	34.7
Blend 7	11.56	4.0	8	61.6
Blend 8	11.50	14.9	5	45.5

ated at inlet pressures (P_3) up to 1.2 MPa (12 atm) and inlet air temperatures (T_3) up to 773 K. The main objective of the research was to examine the extent to which a small-scale model combustor could be used successfully to predict the combustion performance of a full-scale engine combustor. Their study did, in fact, fully vindicate the use of small-scale combustors for this purpose. Furthermore, it resulted in the accumulation of a large amount of flame radiation data acquired over a wide range of combustor operating conditions for three different combustors and several different fuels. Such data lend themselves ideally to any analysis of the effects of fuel combustion on the flame luminosities produced by the combustion of kerosene-type fuels.

A substantial body of evidence on the influence of fuel composition on flame radiation was also generated during a U.S. Air Force program to determine the effects of anticipated future fuels on the hot section lives of existing turbojet engines. Detailed information on all of the relevant physical and chemical properties of the fuels employed in this program are contained in Refs. 27-34. The fuels of relevance to the present study include normal JP4, shale-derived JP4, and four blends of the JP4. The hydrogen content of the test fuels ranged from the JP4 baseline value of 14.5% down to 11.5%. The key chemical properties of these fuels are listed in Table 1.

The general conclusion reached in all of these studies[27-34] was that hydrogen content is the most important fuel property governing flame radiation. For example, for the F100 combustor it was noted that a reduction in hydrogen content from 14.5 to 11.5% caused the flame radiation to double, corresponding to a reduction in liner life of 27%.[32] The measurements carried out on the TF33 and F100 combustors also served to illustrate the separate and important influence of fuel naphthalene content on flame radiation. A fuel with a relatively high concentration of naphthalene (14.9%) produced much higher levels of flame radiation than a fuel of the same hydrogen content containing little naphthalene (4.0%).

Clark[35] used a simplified flameholder geometry to examine the influence of fuel composition on flame radiation. Fuel was injected through a simplex swirl atomizer into the wake region created downstream of a disk flameholder. This system was intended to simulate a conventional diffusion flame burner by creating a fuel-rich recirculation zone near the fuel nozzle.[36] Tests carried out with propane, gasoline, kerosene, diesel oil, and no. 6 oil at combustion pressures ranging from normal atmospheric up to 1.2 MPa (12 atm) indicated that polycyclic acromatics content had a separate influence on flame radiation over and above that due to hydrogen content.

Rosfjord[37] used a tubular generic gas turbine combustor, 12.7 cm in diameter, to study the fuel chemical property influence on radiative heat flux. This burner featured a single pressure-atomizing fuel injector, and fuel physical properties were de-emphasized by selecting fuel injectors that produced well-atomized and hence rapidly vaporizing sprays. The test fuels employed in this study included standard fuels, speciality products, and fuel blends. These fuels were selected to provide wide ranges in the contents of hydrogen, total aromatics, and naphthalene. The results showed that hydrogen content was a better global indicator of chemical property influence than total aromatics or naphthalene content alone. It was also found that fuel naphthalene content is a strong contributor to flame radiation and can dominate the influence of single-ring aromatics. Another interesting conclusion reached by Rosfjord was that the effects of variations in fuel composition on flame radiation are properly represented by the corresponding changes in the fuel smoke point.

Correlation of Flame Radiation Data

The studies described used various fuel properties to correlate rig and engine test data on flame radiation and liner wall temperature. These properties included carbon/hydrogen ratio, hydrogen content, polycyclic aromatic content, total aromatic content, naphthalene content, and smoke point.

Historically, the earliest and most widely used fuel property for the correlation of flame radiation data from gas turbine combustors has been hydrogen content, or C/H ratio. However, some significant departures from this general rule have been observed. For example, Bowden and Pearson[24] observed that fuels containing high concentrations (>20% by mass) of naphthalenes or tetralines exhibited flame radiation characteristics that were more dependent on the presence of such components than on the hydrogen content. Naegeli and Moses,[21] Dodge et al.,[22] and Naegeli et al.[23] also noted that under some combustor operating conditions the flame radiation is affected appreciably by polycyclic aromatics.[21-23] These considerations have led several workers (see, e.g., Ref. 24) to suggest that a combination of hydrogen content with another fuel property such as aromatic content of naphthalene content might provide a better overall measure of combustion quality.

To accommodate the influence of polycyclic aromatics on soot formation and flame radiation, Naegeli and Moses[21] proposed an "effective hydrogen content" of the form

$$H - m(PA) \qquad \text{(parameter 1)}$$

According to Clark,[35] an appropriate value of m for the Naegeli-Moses data would be 0.055. Clark also proposed an alternative fitting parameter with a nonlinear dependency on polycyclic acromaticity of the form

$$H - (PA)^n \qquad \text{(parameter 2)}$$

where $0.1 < n < 0.4$. The main feature common to parameters 1 and 2 is that any increase in fuel polycyclic aromatics causes the "effective" hydrogen content to decline.

Rosfjord's[37] experiments on the influence of fuel composition on flame radiation in combustor liners tended to deemphasize the role of aromatics in soot formation. Rosfjord concluded that the best overall indicators of radiation severity are smoke point, hydrogen content, and naphthalene content. From analysis of his experimental data, he proposed the following two-property parameter, which embodies both hydrogen and naphthalene content, as the best representation of the experimental data:

$$H^{-1.2}(100 - N)^{-0.4} \qquad \text{(parameter 3)}$$

It is of interest to note that Rosfjord considered the quality of this correlation to be "equal to that for a smoke point correlation, both of which are superior to a solely hydrogen content correlation."

In a recent companion study on the influence of fuel composition on soot formation in gas turbine combustors,[38] the present authors obtained an excellent correlation of the experimental data by using a parameter that combines naphthalene content with smoke point to yield

$$SP^{-0.92}(100 - N)^{-0.4} \qquad \text{(parameter 4)}$$

It is clearly of interest to examine the extent to which this parameter is also capable of correlating experimental data on the influence of fuel composition on flame radiation.

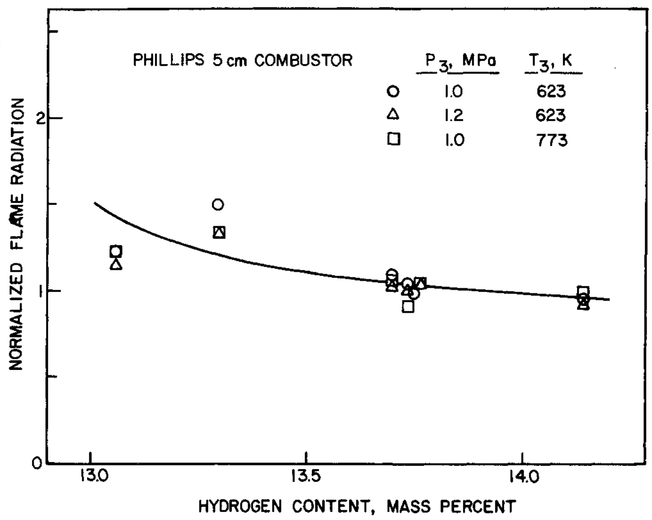

Fig. 1 Correlation of flame radiation with hydrogen content.[26]

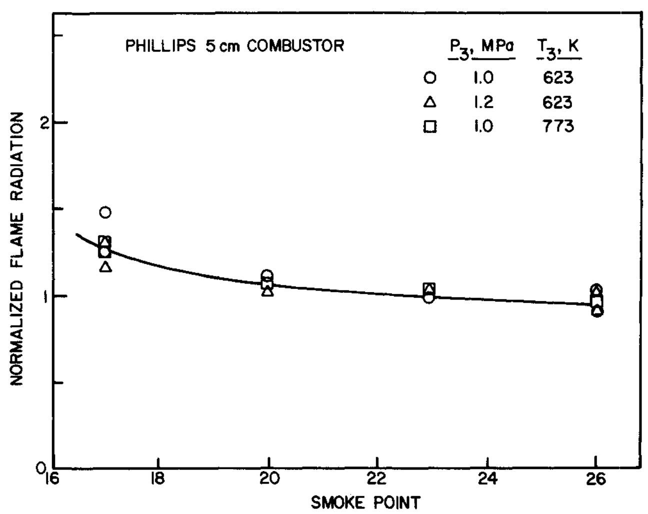

Fig. 2 Correlation of flame radiation with smoke point.[26]

The correlations shown in Figs. 1-11 were obtained using published data on flame radiation and liner wall temperature for several gas turbine and model combustors. A Phillips 5-cm model combustor was used by Bowden et al.[26] to acquire the flame radiation data shown in Figs. 1-3. Basically, this combustor is a straight-through tubular type, 5 cm in diameter and 21.5 cm in length, fitted with a simplex pressure-swirl atomizer. It has been used extensively for aviation fuel research in the areas of flame radiation and exhaust smoke. Measurements of flame radiation were made for seven different kerosene-type fuels using a scanning infrared emission/absorption technique. The combustor operating conditions incorporated two levels of inlet air pressure and temperature, as indicated in Figs. 1-3. All of the data shown in these figures were obtained with the combustor operating at an overall air/fuel ratio of 60.

As discussed earlier, the property most widely used to indicate a fuel's propensity to soot formation and flame radiation is hydrogen content. Figure 1 demonstrates a less than satisfactory correlation of radiation data with hydrogen content. Figure 2 shows the same experimental data plotted against smoke point. The correlation achieved is clearly better than for hydrogen content. Further improvement in correlation is obtained by plotting flame radiation against parameter 4, as shown in Fig. 3.

The Phillips model combustor was also used by Naegeli and Moses[21] to examine the effect of fuel molecular structure on soot formation and flame radiation. Six test fuels were blended with essentially equal hydrogen contents (12.8%) but with as much variation in composition as possible. Flame measurements were made through a sapphire window located at the end of the primary zone. The results of this study showed that fuels containing high concentrations of polycyclic aromatics formed more soot than would be expected from a hydrogen content correlation. The inadequacy of hydrogen content as a correlating parameter for such fuels is clearly demonstrated in Fig. 4, which also shows that a reasonably good correlation of the same data is provided by parameter 4.

Three important engine operating conditions for the J79 combustor are represented by the data shown in Fig. 5. The J79 engine employs a turboannular combustion system with 10 combustion liners. The 10 fuel nozzles are of the dual-orifice, pressure-atomizing type. The flame radiation data shown in Fig. 5 were obtained with a total radiation pyrometer located in the primary combustion zone. It is clear from Fig. 5 that hydrogen content provides a less than satisfactory correlation of the experimental data, especially at the highest levels of radiant heat loading on the liner walls. Figure 6 shows the same experimental data when plotted against parameter 4. Comparison of Figs. 5 and 6 shows clearly that parameter 4 is much

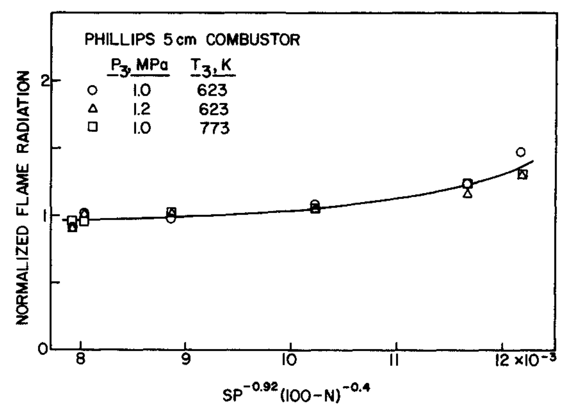

Fig. 3 Correlation of flame radiation with a combined smoke point-naphthalene parameter.[26]

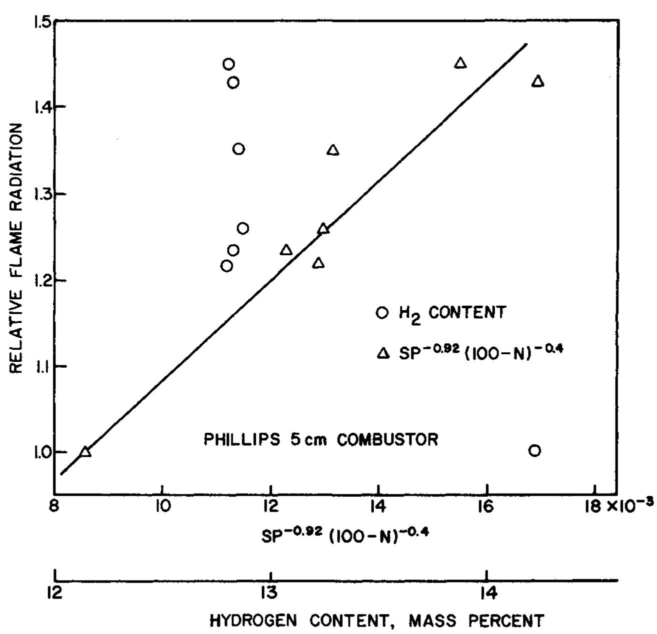

Fig. 4 Comparison of correlations obtained with hydrogen content and combined smoke-naphthalene parameter.[21]

superior to hydrogen content in regard to its ability to correlate the J79 data.

A similar situation exists in regard to the TF41 data presented in Figs. 7 and 8. The TF41 combustor is a turboannular design incorporating 10 cylindrical combustion liners. Each liner contains a pressure-atomizing, dual-orifice fuel nozzle. In a test program conducted by Vogel et al.,[29] the influence of fuel composition on peak liner wall temperature was examined. The results obtained at combustor inlet conditions corresponding to engine operation at dash, cruise, and idle are shown in Figs. 7 and 8. As the convective heat transfer from the flame to the liner walls is essentially the same for all fuels, any observed variations in liner wall temperature with change in fuel composition can be attributed directly to variations in flame radiation. Thus, when used in this manner, measurements of peak liner wall temperature can provide useful guidance on how flame radiation is affected by various relevant factors, in this case variation in fuel composition. In Fig. 7 the measured values of peak liner wall temperature are plotted against hydrogen content; in Fig. 8 the same data are plotted against parameter 4. Comparison of these two figures shows that parameter 4, which combines smoke point and naphtha-

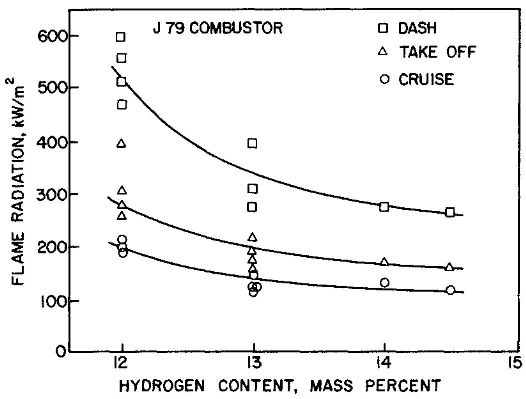

Fig. 5 Correlation of flame radiation with hydrogen content.[27]

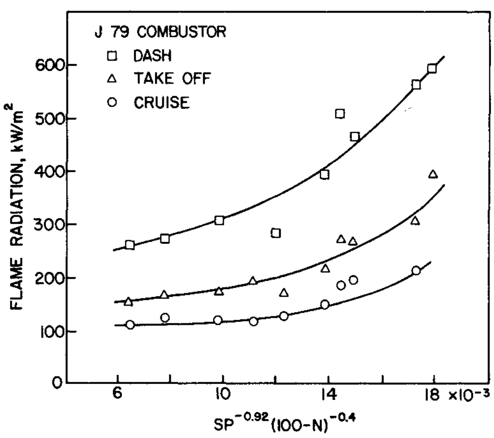

Fig. 6 Correlation of flame radiation with a combined smoke point-naphthalene parameter.[27]

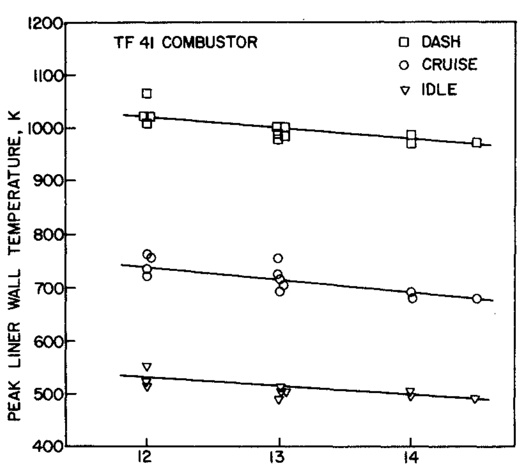

Fig. 7 Correlation of liner wall temperature with hydrogen content.[29]

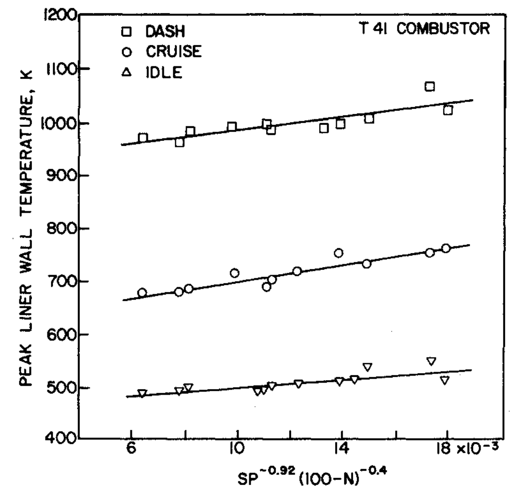

Fig. 8 Correlation of liner wall temperature with a combined smoke point-naphthalene parameter.[29]

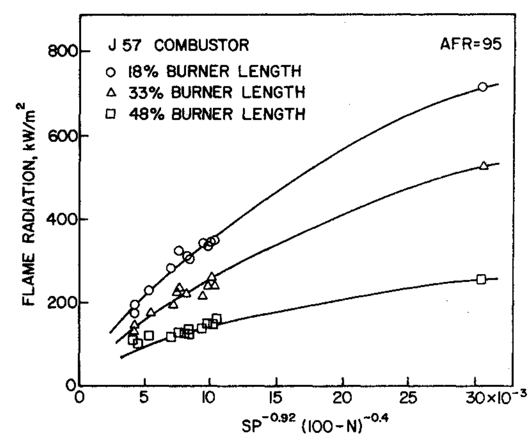

Fig. 9 Correlation of flame radiation for a J57 combustor. AFR = 95.[16]

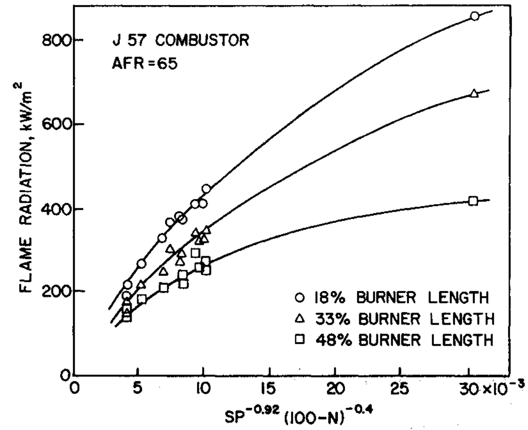

Fig. 10 Correlation of flame radiation for a J57 combustor. AFR = 65.[16]

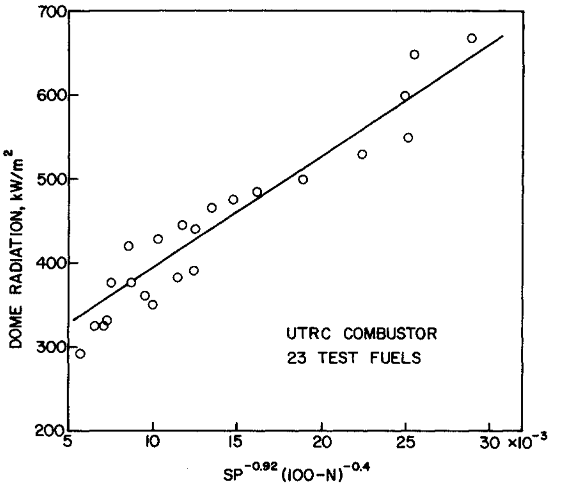

Fig. 11 Correlation of dome radiation with a combined smoke point-naphthalene parameter.[37]

lene content, gives a better representation of the influence of fuel composition on flame radiation than does hydrogen content alone.

Schirmer et al.[16] used a J57 aircraft gas turbine combustor to study the effect of monocyclic vs polycyclic aromatic components in kerosene-type fuels. Total flame radiant energy was measured at three different axial distances downstream of the pressure-swirl fuel nozzles, as indicated in Figs. 9 and 10, in which flame radiation is plotted against parameter 4 for three different values of burning length. Both figures demonstrate a very satisfactory correlation between flame radiation and parameter 4. Unfortunately, the chemical properties provided for these test fuels do not include hydrogen content, so that no comparison between hydrogen content and parameter 4 can be made.

Rosfjord[37] used regression analysis to derive parameter 3. This two-property parameter, which embodies both hydrogen and naphthalene content, was found to provide an accurate representation ($R^2=0.93$) of his experimental data on liner dome radiation obtained with a large number of test fuels. These same data are shown plotted against parameter 4 in Fig. 11. Regression analysis of these data yields a value for R^2 of 0.92, as compared with 0.93 for parameter 3. This result is considered satisfactory because it demonstrates that parameter 4 can not only correlate successfully a wide body of experimental data on soot concentration and flame radiation, as evidenced in Ref. 38 and in this paper, but its ability to correlate Rosfjord's dome radiation data is comparable to that of parameter 3, which was designed specifically to match these particular data.

Summary

Because of the normal limitations on space, most of the results obtained using ASTM Smoke Point as the correlating parameter have, of necessity, been omitted from this paper. Selection of the material to be included has tended to favor hydrogen content and parameter 4—the former because it is the most widely used, and the latter because it is considered to be the best overall indicator of a fuel's propensity for soot formation and flame radiation. However, it is noteworthy that in all of the cases examined (see, e.g., Figs. 1 and 2), the smoke point gave a better representation of flame radiation data than hydrogen content. Several investigators, including Rosfjord[37] and Chin and Lefebvre,[38] have demonstrated that soot-forming tendencies are represented better by smoke point than by hydrogen content. However, parameters 3 and 4 both reflect Rosfjord's views on the importance of including a term to represent fuel naphthalene content.

In conclusion, it can be stated that although hydrogen content provides a useful general indication of the influence of fuel composition on luminous flame radiation, a better fit to the measured values can be achieved by using smoke point as the correlating parameter. The best representation of the experimental data is provided by the following two-property parameter, which embodies both smoke point and naphthalene content: flame luminosity $=f[SP^{-0.92}(100-N)^{-0.4}]$.

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