Int. J. Heat Mass Transfer. Vol. 27, No. 9, pp. 1493–1510, 1984
Printed in Great Britain

0017-9310/84 $3.00 + 0.00

Flame radiation in gas turbine combustion chambers

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(*Received* 23 *February* 1984)

Abstract—A brief description of the nature of flame radiation in gas-turbine combustors is followed by a discussion on the methods and models available for estimating nonluminous and luminous emissivity. Since luminous radiation emanates from soot particles in the flame, consideration is given to the processes of soot formation and soot oxidation, and to the influence of chemical composition on the soot-forming tendencies of fuels. Experimental data on the effects on flame radiation of variations in the combustor operating conditions of pressure, temperature, velocity, and fuel/air ratio are discussed. The important influences on flame radiation of fuel properties and fuel spray characteristics are also considered.

INTRODUCTION

It is now well established that in gas turbine combustion chambers a large proportion of the total heat flux 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 high and mixing of fuel and air is inadequate, 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 black bodies 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 process of flame radiation in gas turbine combustors has not been subjected to extensive experimental investigation. In fact, the number of reported studies is surprisingly small. This is due partly to the formidable experimental difficulties involved, especially at high combustion pressures, but another reason is that 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 early 1970s originated from the growing body of evidence on the performance penalties associated with film cooling, such as deterioration of temperature pattern factor and combustion inefficiency 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 liner-wall cooling to an absolute minimum. The determination of this minimum quantity for any given combustor depends, of course, 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 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 transfer from the flame to the liner. The impact of the latter is emphasized by recent studies which show 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 prediction 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.

In recent years a number of excellent reviews have

NOMENCLATURE

c	constant in equation (18)
c_2	Planck's second constant
C_{CO_2}	correction factor for carbon dioxide
C_{H_2O}	correction factor for water vapor
C_F	fuel concentration
C_{O_2}	oxygen concentration
C_s	soot concentration
C/H	carbon/hydrogen ratio by mass
E	activation energy
f_v	volume fraction of soot particles
I_0	initial beam intensity
I_L	beam intensity after distance L
L	path length [m]
l	mean beam length [m]
K	extinction coefficient, or absorption coefficient
k, n	infrared-average optical constants of soot particles
P	total pressure [kPa]
p	partial pressure [kPa]
q	fuel/air ratio by mass
R	radiative flux, or gas constant
T	temperature [K]
T_0	initial temperature [K]
T_w	liner wall temperature [K].

Greek symbols

α_g	gas absorptivity
ε_g	nonluminous gas emissivity
ε_s	soot emissivity
ε_T	total emissivity
ε_w	liner wall emissivity
ε_{CO_2}	emissivity due to CO_2
ε_{H_2O}	emissivity due to H_2O
σ	Stefan–Boltzmann constant
ϕ	equivalence ratio
Ω	specific gravity at 293 K.

been published on the subject of flame radiation [3–5]. The present work is confined to flame radiation in gas turbine combustors. Methods of estimating nonluminous radiation are discussed together with various analytical models for flame radiation in enclosures, but attention is focused mainly on the factors that govern the total radiative heat transfer to the liner wall, and the impact on radiative heat flux of combustor design features, combustor operating conditions, fuel composition and fuel spray characteristics. As luminous flame radiation is closely linked to soot formation, some consideration is given to the mechanisms of soot formation and soot oxidation, and to the effect of changes in fuel specifications on soot formation and flame radiation in gas turbine combustion chambers.

NONLUMINOUS RADIATION

The nature of the nonluminous radiation emitted by hot gases has been described by Gaydon [6], Tourin [7] and Penner [8]. A characteristic of gas radiation is that it occurs in the form of band spectra. Although solids emit heat at all wavelengths throughout the spectrum, the emissions of a gas are essentially discontinuous and consist of a few narrow bands dispersed over the infrared spectrum. For each molecular specie, radiation occurs at a wavelength that corresponds to the vibration frequency of the atoms within the molecule. As there are several possible modes of vibration, radiation is emitted at a number of different wavelengths. The number, widths, and absorptions of the various bands depend on gas composition and on the pressure, temperature, and thickness of the gas volume.

In a gas turbine combustion chamber the radiating species are typical of those found in all hydrocarbon flames. The products of combustion consist mainly of H_2O, CO_2, and N_2, along with smaller amounts of CO, NO, NO_2, O_2, H_2, and other minor species. In nonluminous flames the banded spectra from H_2O and CO_2 are the most prominent feature at temperatures up to about 3000 K. The strongest emission bands for H_2O are centered at 1.4, 1.9, 2.7, 6.3, and 21 μm. CO_2 radiates strongly around 2.7, 4.3, and 15 μm. At higher temperatures H_2O and CO_2 are depleted by dissociation, but radiation from diatomic molecules, notably CO, is increased. Although CO can contribute significantly to the emission and attenuation of radiation within flames, its contribution is localized and is of secondary importance in evaluating radiative fluxes. The contributions of SO_2 and NO_x can be neglected because of their low concentrations. Moreover, gases with symmetrical molecules, such as H_2, O_2, and N_2, give no appreciable radiation, even at the highest temperatures.

The fixed location of the emission bands means that the bands gain or lose importance as the temperature changes. Another effect of temperature is to fill up the vibration bands with fine emission lines due to rotational transitions which may broaden and overlap due to various 'broadening' mechanisms and thus become significant [9]. Another important mechanism at low temperatures is collision broadening [10]. Water vapor is pressure-broadened more than CO_2, due to the larger spacings between emission lines in H_2O.

Emissivity also depends on the size and shape of the gas volume, which are usually combined into a single dimension termed the 'mean beam length'. The longer the mean beam length, the higher will be the emissivity of the gas. Thus the main factors which govern the nonluminous radiation of gases are pressure, temperature, composition, and beam length.

Calculation of nonluminous radiation

The rate of heat transfer by nonluminous radiation from a gas to its enclosure is given by [11]

$$R = 0.5\,\sigma(1+\varepsilon_w)(\varepsilon_g T^4 - \alpha_g T_w^4) \qquad (1)$$

in which ε_w is dependent on the material, temperature, and degree of oxidation of the wall. Approximate mean values of ε_w at typical liner wall temperatures for Nimonic, stainless steel, and mild steel are 0.7, 0.8, and 0.9, respectively.

Investigation over a wide range of values has shown [12] that to a sufficiently close approximation

$$\frac{\alpha_g}{\varepsilon_g} = \left(\frac{T}{T_w}\right)^{1.5}. \qquad (2)$$

Hence, equation (1) may be rewritten as

$$R = 0.5\,\sigma\,(1+\varepsilon_w)\varepsilon_g T^{1.5}(T^{2.5} - T_w^{2.5}).$$

The bulk or mean gas temperature, T, is obtained as the sum of the chamber entry temperature, T_0, and the temperature rise due to combustion, ΔT_{comb}

$$T = T_0 + \Delta T_{comb}. \qquad (3)$$

ΔT_{comb} may be derived from standard temperature-rise curves. When these curves are used, the appropriate value for the fuel/air ratio is the product of the local fuel/air ratio and the local level of combustion efficiency. Most heat-transfer calculations are carried out at high pressures, for which it is reasonable to assume a combustion efficiency of 100%. However, this does not apply to the primary zone, where the level of combustion efficiency rarely exceeds 90%, even at the highest pressures.

Hottel's well-known and well-utilized gas emissivity charts for CO_2 and H_2O have long been the traditional means for estimating the total nonluminous radiation from combustion gases [13]. In these charts, as shown in Figs. 1 and 2, emissivity is plotted against gas temperature for different values of the product of the partial pressure, P, and the beam length, l, for a 'total' pressure of 100 kPa (i.e. 1 atm). The 'total' pressure here is the sum of all the partial static pressures and should not be confused with the stagnation pressure. The beam length is determined by the size and shape of the gas volume. For most practical purposes it is given to sufficient accuracy [11] by the expression

$$l = 3.4\,\frac{\text{volume}}{\text{surface area}}. \qquad (4)$$

For tubular systems the above expression yields values of beam length ranging from $0.6D_L$ to $0.9D_L$, depending on the length/diameter ratio of the liner. For a long annular liner, $l \simeq 0.9D_L$.

For a typical kerosine of the form C_nH_{2n}, for a fixed 'total' pressure, the partial pressures vary with fuel/air ratio as shown in Fig. 3. Up to the region near stoichiometric, where dissociation intervenes, this variation may be expressed to a close approximation [12] by

$$\frac{p}{P} = \frac{2.1q}{1+1.05q} \qquad (5)$$

for both carbon dioxide and water vapor.

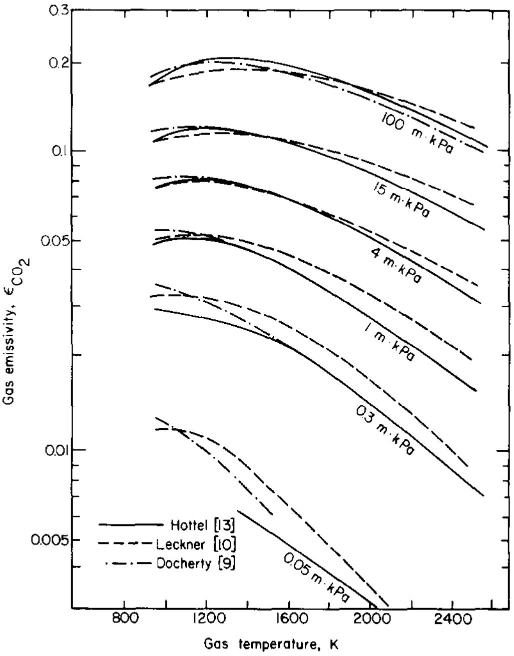

FIG. 1. Comparison of models for carbon dioxide emissivity.

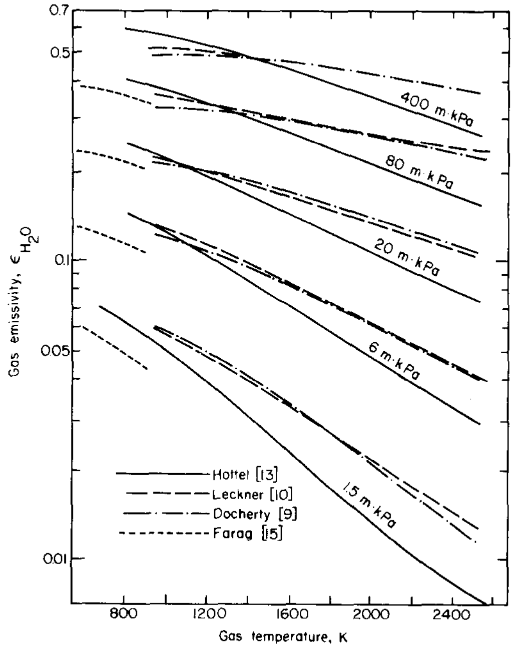

FIG. 2. Comparison of models for water vapor emissivity.

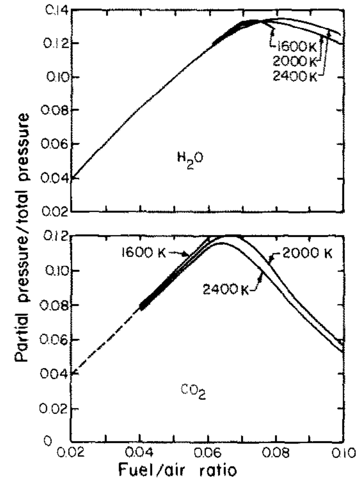

FIG. 3. Variation of partial pressure of carbon dioxide and water vapor with fuel/air ratio [12].

More general empirical formulae for estimating p_{CO_2} and p_{H_2O} have been provided by Kunitomo and Kodama [14] as

$$P_{CO_2}/P = 0.175 - 0.075/\phi + 0.033\Omega \qquad \text{for } \phi < 1.1 \quad (6)$$

$$= 0.092 + 0.038\Omega - 2.619(1.01 - \Omega) \times (1.05 - 1/\phi)^2 \qquad \text{for } \phi \geqslant 1.1 \quad (7)$$

$$P_{H_2O}/P = 0.259 - 0.068/\phi - 0.0783\Omega \qquad \text{for } \phi \geqslant 1.05 \quad (8)$$

$$= 0.126 - 0.72[1/\phi + 0.887\Omega - 1.724 - 1.42(\Omega - 0.805)^2]^2 \qquad \text{for } \phi > 1.05 \quad (9)$$

where ϕ is the equivalence ratio and Ω is the specific gravity of the fuel at 293 K.

The values of ε_{CO_2} and ε_{H_2O} as read off Hottel's charts must first be multiplied by the pressure-broadening factors, C_{CO_2} and C_{H_2O}, respectively, before being added together to obtain the total nonluminous emissivity [13]. The original work by Hottel included total pressure correction factors for both gases, but the range of pressures covered was far too low to meet the needs of modern gas turbines. More recent work by Farag [15] has yielded correction factors for CO_2 and H_2O at the higher levels of pressure of interest for gas turbines. At these conditions the correction factor for H_2O is given by [16]

$$C_{H_2O} = 1.44 + P[0.00054/T^{0.5} - 0.002ql]. \quad (10)$$

However, inspection of Farag's graphs reveals that in the regions of main interest the values of C_{CO_2} and C_{H_2O} tend to remain fairly constant at around 1 and 1.42, respectively.

Since the emission bands of CO_2 and H_2O overlap, each gas absorbs radiation from the other. When both are present, the total radiation emitted is less than the sum of that due to each of the two gases acting alone. Thus, after the emissivities of CO_2 and H_2O are obtained separately, a correction for mutual absorption, $\Delta\varepsilon$, must be deducted. For the liquid fuels of gas turbine interest Hottel's charts [13] suggest that $\Delta\varepsilon$ is independent of gas temperature above 1200 K, where $\Delta\varepsilon$ remains constant at 0.054. Although this is true for most practical purposes, $\Delta\varepsilon$ does in fact vary slightly with temperature in this range, its value rising with increase in temperature from 1200 to around 1600 K, after which it declines slowly with further increase in temperature [15, 17].

Thus for combustion pressures below 1 MPa (10 atm) the nonluminous emissivity is given by

$$\varepsilon_g = \varepsilon_{CO_2}C_{CO_2} + \varepsilon_{H_2O}C_{H_2O} - \Delta\varepsilon C_{CO_2}C_{H_2O}. \quad (11)$$

All the parameters in the above equation can be obtained (sometimes a little extrapolation is called for) directly from Hottel's charts [13]. For high combustion pressures (>1 MPa) and temperatures (>1200 K), where $C_{CO_2} \simeq 1.0$, $C_{H_2O} \simeq 1.42$, and $\Delta\varepsilon \simeq 0.054$, equation (11) simplifies to

$$\varepsilon_g = \varepsilon_{CO_2} + 1.42\varepsilon_{H_2O} - 0.077. \quad (12)$$

Where a large number of emissivity calculations are involved, using Hottel's charts to obtain ε_{CO_2} and ε_{H_2O} can be tedious and time consuming. To alleviate this problem various approximate formulae for nonluminous emissivity have been proposed, of which the most widely quoted in gas turbine literature is the following due to Reeves [18]

$$\varepsilon_g = 1 - \exp[-290P(ql)^{0.5}T^{-1.5}]. \quad (13)$$

Unfortunately this expression is valid only for gas pressures below 5 atm. For higher pressures more accurate values are given by the empirical formula [16].

$$\varepsilon_g = (0.15 - 0.00005T)(2Pql)^{(0.20 + 0.00015T)}. \quad (14)$$

This expression yields values of ε_g which agree closely with the corresponding values from the updated charts for ε_{CO_2}, ε_{H_2O}, C_{CO_2}, C_{H_2O}, and $\Delta\varepsilon$ due to Farag [15], as described by Sarofim *et al.* [17]. It is considered valid for pressures below 4000 kPa (40 atm), temperatures between 1200 and 2400 K, and fuel/air ratios weaker than stoichiometric.

Influence of fuel chemistry

The composition of the combustion products and, in particular the relative proportions of CO_2 and H_2O varies with the carbon/hydrogen ratio of the fuel. According to Sarofim [19] emissivities increase with hydrogen content up to a value of H/(C+H) of around 0.85. For a change from a petroleum-derived distillate fuel [$(CH_2)_n$ or H/(C+H) = 0.67] to a highly aromatic fuel [$(CH)_n$, or H/(C+H) = 0.5] the emissivity would decrease by just a few percent at high combustion pressures. Thus, for the various alternative fuels of interest for gas turbine applications, the influence of fuel type on nonluminous radiation is expected to be quite small.

Emissivity models

Hottel's emissivity charts are simple to use and are considered accurate in the regions supported by experimental data. However, they are not well suited for mixtures of more than two radiating species, and correction factors for spectral overlap when dealing with mixtures of various gases do not always exist. During the last several decades many attempts have been made to alleviate this situation by providing a more general and fundamental spectral basis for gaseous radiation. The results of these extensive theoretical and experimental studies have been reviewed by de Ris [3], Tien and Lee [4], Viskanta [5], and Docherty [9], so only their main features are discussed below.

In theory it might be possible to predict the positions and strengths of all the absorption lines in the spectrum for a gas, and this is the objective of the 'just overlapping line' model of Penner and Varanasi [20]. A less fundamental but more practical approach is the so-called 'narrow-band' model which divides the thermal radiating spectrum into many small intervals for each radiating specie. Within each interval the spectral lines are assumed to have random or regularly spaced locations, while their strengths are assumed to follow an exponential or uniform probability distribution [3]. Ludwig and coworkers [21, 22] have provided the spectral constants needed to calculate for each contributing interval the emission and absorption of most of the important gases over pressures and temperatures of interest in combustion systems. Unfortunately, calculations using the narrow-band model require a massive amount of input data and large amounts of computer time which makes the model impractical for most engineering applications.

Simpler approaches based on analytical approximations to the results of the narrow-band model have been developed for CO_2–H_2O mixtures by Leckner [10] and Taylor and Foster [23]. The results of Leckner's calculations for CO_2 and H_2O are plotted in Figs. 1 and 2. They demonstrate close agreement with Hottel's charts except at high temperatures and long beam lengths, where Hottel's overlap corrections underpredict the emissivity [3]. Foster and Taylor's model also agrees well with Hottel's empirical correlations but is restricted to low-pressure applications which are of little interest for the gas turbine.

Following a model suggested by Sarofim *et al.* [17], Farag [15] attempted to formulate real-gas emission by the radiation of a number of gray gases. This allows the emissivity–*pl* relationship for any real gas to be approximated by the weighted sum of a sufficient number of gray gases. Farag's results for CO_2 and H_2O are included in Figs. 1 and 2, respectively. The agreement of the model with the reference emissivities [17] is clearly very satisfactory, but it should be noted that the results presented for H_2O are confined to temperatures below 1000 K.

During the past two decades Edwards and coworkers [24–26] have developed the exponential 'wide-band' model for radiation from combustion gases. This model takes advantage of the fact that infrared radiation from each specie is concentrated into up to six wide-band spectral regions associated with its principal vibrational transitions. The numerous individual spectral lines within these vibrational bands are associated with different rotational transitions. The method allows the width of a given band of gas species to be calculated for any mixture at any temperature and pressure. Some of the species overlap in their absorption bands and this must be accommodated to avoid overestimating the total mixture emissivity.

Best-fit parameters have been provided for the wide-band model by Edwards and Balakrishnan [25] for the important gases over broad ranges of pressure and temperature. The model has been used successfully by Docherty [9] whose results for CO_2 and H_2O appear in Figs. 1 and 2, respectively. Modak [27] has since revised the wide-band parameters for H_2O which improves the model's accuracy at temperatures below 1000 K. De Ris [3] has shown that Modak's improved wide-band model agrees closely with Hottel's correlations despite its completely independent source of data.

In summary the wide-band model is applicable under widely different physical conditions, and mixtures of CO_2, H_2O, CO, NO, SO_2, and CH_4 can easily be handled. Moreover, it is simple to use and appears to have the advantages of accuracy and generality possessed by the more detailed narrow-band model for combustion situations [3]. Further information on the wide-band model, and other models of relevance to combustion systems, is contained in the review articles of de Ris [3], Docherty [9], and Tien and Lee [4].

Radiative flux models

In gas turbine combustors a significant proportion of the total heat transferred from the combustion gases to the liner is by radiation. Thus accurate assessments of radiant heat flux are an essential prerequisite for the prediction of liner wall temperatures and liner durability.

An additional incentive for establishing methods for predicting radiative exchange in gas turbine combustors stems from their potential contribution to the control and reduction of pollutant emissions. Advanced modeling techniques are being developed for predicting the emissions of carbon monoxide, unburned hydrocarbons, and oxides of nitrogen, but these methods require an accurate description of gas temperature distributions in all regions of the combustor. As the local temperature of any small segment within the flame zone is influenced strongly by the amount of radiant heat it exchanges with neighboring segments and with the liner wall, it follows that accurate assessments of pollutant emissions necessitate fairly precise knowledge of radiant heat-transfer rates.

These considerations have led in recent years to the development of several models for flame radiation in furnaces and combustion chambers. Detailed information on these models is provided by Viskanta [5], and in the following sections consideration is given only to those which appear most relevant to gas turbine combustors.

Perhaps the most widely used method for calculating radiative transfer in non-isothermal enclosures is the 'zone' method as developed by Hottel and Cohen [28] and Hottel and Sarofim [29]. Application of the zone method requires the whole gas volume to be divided into a number of smaller volumes, each with uniform properties such as temperature, composition, emissivity and transmissivity. The radiation from each volume to the liner wall can then be calculated, provided their relative geometrical orientation is known. The method requires only the solution of a set of simultaneous algebraic equations; however, the computer time involved may be so lengthy as to seriously restrict the number of zones into which the total combustion volume is divided. In addition to limiting the accuracy of the method, this could also lead to incompatibility between the coarse grid used for radiative transfer calculations and the finer grids required for associated fluid-mechanics calculations [5].

The Monte-Carlo method is also based on the solution of the simultaneous algebraic equations of three-dimensional (3-D) heat transfer, but the calculations are greatly simplified by treating the radiative exchange between gases and/or surfaces in a probabilistic manner. This allows the number of zones into which the combustion volume is subdivided to be greatly increased. The total energy emitted by each zone is divided into several beams each of which is emitted with equal energy in a random direction from a random location in the zone. As each beam travels through the gas its attenuation is described by Beer's law. If its energy is not totally absorbed by the combustion gases before it reaches a wall surface, the remaining energy is reflected back into the combustion volume in a random direction. The calculation continues until the beam energy is completely absorbed [30].

The merits and shortcomings of the Monte-Carlo method have been discussed by Viskanta [5]. Its main advantages lie in its flexibility, and its ability to be applied to complex geometries. Absorption and scattering by particles in the flame can be accounted for adequately. Its principal drawback is that it is time consuming to the extent that it offers no economic advantage over the zonal method. Furthermore, it is incompatible with the numerical techniques used for fluid flow and temperature field calculations because they require different numerical algorithms.

In the flux methods the solid angular distribution of radiation intensity is subdivided into several smaller solid angles. Subsequent integration of the equation of radiant energy transfer over each of the smaller solid angles leads to a set of simultaneous partial differential equations for the unknown intensities, which may be solved in parallel with the differential equations representing balances in mass, momentum, energy, and chemical composition [31].

Radiation in an absorbing–emitting gray gas within a cylindrical enclosure is normally represented by a four-flux model of the radiative field, with two fluxes in each of the radial and axial directions. Two-flux methods have been advocated which involve the use of a one-dimensional (1-D) space grid rather than the two-dimensional (2-D) grid required for the four-flux representation [31]. This simpler approach reduces computational complexity and allows considerable economies in computer time, but the accuracy is thereby greatly reduced.

Spalding [32] has formulated four- and six-flux methods, and extensions of the two-flux method to multi-flux and nongray emitting–absorbing media are also discussed by Siddall [33]. One reported example of the use of the four-flux method demonstrated satisfactory prediction of wall temperatures, although radiation fluxes were underestimated [34]. A six-flux model is currently in use at the Garrett Turbine Engine Company [35].

The reasons for the inaccuracies in flux methods are (a) the radiant flux is divided into too few directions (2, 4, or 6 being small for many applications), and (b) the fluxes in the different directions are unrealistically independent of each other. Another limitation of the flux models is that their extension to general curvilinear coordinates for handling complex geometries is rather cumbersome [35].

The 'discrete-transfer' method proposed by Lockwood and Shah [36] is similar to the Monte-Carlo method in that it is based on the solution of representatively-directed beams of radiation within the combustor. However, in this method the ray directions are not random but are specified in advance, and are solved only between two boundary walls. The method is economical, easy to apply, and has potential for high accuracy. It can be adapted to a wide range of geometries and is designed to be coupled to fluid flow solutions. The method appears to be well suited for gas turbine combustors and one such application has been reported [35].

LUMINOUS FLAMES

At atmospheric pressure, the soot particles formed in combustion contribute a continuum in the visible spectral range, thereby producing a luminous flame, but usually they are too small in size to radiate appreciable energy in the important infrared region. With increase in pressure, the continuous radiation increases in intensity and the molecular bands become less pronounced. At the high levels of pressure encountered in modern gas turbines, the soot particles can attain sufficient size to radiate as black bodies in the infrared region, and the flame is then characterized by a predominance of continuous radiation.

It has been found that when a parallel beam of radiation passes through a system of particles the strength of the beam declines exponentially according to the relationship [37]

$$I_L/I_0 = \exp(-KL) \tag{15}$$

where I_L is the intensity of the beam after travelling a distance L through the system of particles, I_0 is the intensity at $L = 0$, and K is the extinction coefficient having the dimensions of reciprocal length. For small particles ($\pi D/\lambda < 1$) scattering of radiation is small in comparison with absorption and K becomes the absorption coefficient.

In recent years a subject of debate has been whether or not luminous flames can be regarded as spectrally gray [3]. This is an important issue, since the gray assumption facilitates the reporting of flame property data and also greatly simplifies engineering calculations of radiative heat transfer.

If emissivity can be assumed equal to absorptivity, then the emissivity of a soot-bearing medium may be defined as

$$\varepsilon_s = (I_0 - I_L)/I_0. \tag{16}$$

Substitution from equation (15) leads to the result

$$\varepsilon_s = 1 - \exp(-KL). \tag{17}$$

Yuen and Tien [38] have shown that equation (17) represents an excellent approximation (within 7%) to exact closed-form expressions for soot emissivity based on nongray analysis, provided that K is given as

$$K = 3.6\frac{cT}{c_2} \tag{18}$$

where c_2 is Planck's second constant, and c is given by

$$c = 36\pi f_v \frac{n^2k}{[n^2-(nk)^2+2]^2+4n^2k^2}$$

where f_v is the volume fraction of soot particles and n and k are the infrared-average optical constants of soot particles. It is interesting to note that soot emission does not depend on the separate values of the fundamental soot parameters, f_v, n, and k, but depends only on the value of the effective soot-concentration parameter c.

The optical constants are expected to be a function of the carbon/hydrogen ratio of the soot and its temperature history [19]. Values of k and n for soots produced in propane and acetylene diffusion flames have been measured by Dalzell and Sarofim [39]. The molar carbon to hydrogen ratio of these soots was found to vary from 4.6 to 14.7, whereas the refractive indices, which depended on wavelength, were found to be practically the same for both extremes. This is an important result because it suggests that indices of refraction of all soots should be about the same [40]. Additional data on optical constants for graphites, pyrographites, and soots are contained in refs. [41–43], respectively, and appear in graphical form in ref. [19]. According to Sarofim [19] the available data are considered to be sufficiently representative of soots in flames to provide a basis for estimates of the luminous soot contribution to flame radiation.

From a practical standpoint, however, the value and importance of equation (18) is that using this simple expression an experimentalist can determine the soot-emission coefficient, K, and the mean temperature, T, from extrapolation of simple, simultaneous measurements of the flame emissivity, ε, and the path length [44, 45]. Also, from a theoretical viewpoint the assumption of a homogeneous gray mixture permits the calculation of radiative heat transfer in terms of the characteristic flame shape and the single dimensionless optical depth parameter KL, where L is some characteristic length for a particular geometry. This assumption makes such calculations very much easier [3, 4].

Gray-soot behavior in luminous flames has been observed by Markstein [46] for gaseous fuels, Buckius and Tein [44] for polymer fuels, and Hagglund and Pearson [45] for wood fuels.

Total emissivity of luminous flames

On the basis of gray-soot analysis the total emissivity of a soot-bearing flame is given as

$$\varepsilon_T = \varepsilon_g + \varepsilon_s - \varepsilon_g\varepsilon_s \tag{19}$$

where ε_s is the soot emissivity and ε_g is the emissivity of the radiating gases alone. The total emissivity of luminous flames predicted by equation (19) is found to give excellent agreement with calculations based on the more precise nongray analysis [38]. Further support for the validity of equation (19) has been provided by de Ris [3], who demonstrated close agreement between predictions of emissivity based on Leckner's model [10], and the pure-gas model of Taylor and Foster [47], coupled with equation (19), with the exact narrow-band calculation of Taylor and Foster [23] for a soot–gas mixture.

Thus for regions of the flame in which reasonable homogeneity prevails, extensive spectral soot calculations are unnecessary. Any one of the models for gas mixtures proposed by Docherty [9], Farag [15], Leckner [10] or Modak [48], together with equations (17) and (19), is much simpler to use and is quite adequate for most practical purposes.

In essence the total emissivity of a homogeneous luminous flame can be expressed in a relatively simple form involving only five parameters, the temperature, T, the pathlength, L, the soot-emission coefficient, and the partial pressures of the two main participating gases, H_2O and CO_2 (which, in turn, are dependent on T and L, as well as on the pressure and fuel/air ratio of the burning zone). When attempting to estimate the flame emissivities for a new combustor design all these parameters are either known, or can be calculated fairly accurately, with the exception of K. At the present time no quantitative basis exists for linking K to the size and geometry of the combustor, the chemical and physical properties of the fuel, the fuel spray characteristics, and the pressure, temperature, turbulence, and fuel/air ratio of the flame zone.

To alleviate this situation Lefebvre and Herbert [12] proposed the notion of a 'luminosity factor' L_f to account for soot radiation from flames. Insertion of L_f into equation (13) gives

$$\varepsilon = 1 - \exp\left[-290 P L_f (ql)^{0.5} T^{-1.5}\right]. \quad (20)$$

The luminosity factor is an empirical correction introduced to obtain reasonable agreement between experimental data on gas radiation and predictions from equation (20). Experiments have shown that the luminosity factor depends largely on the carbon/hydrogen mass ratio of the fuel, C/H, and to a lesser extent on the combustion pressure [12, 49–51] and the type of fuel injector employed [52]. The value of L_f can be expected to decrease downstream of the primary combustion zone because of gradual burnout of the soot particles.

The original equation [12] for L_f is

$$L_f = 7.53(\mathrm{C/H} - 5.5)^{0.84}. \quad (21)$$

Later the following expression was suggested by Kretschmer and Odgers [53]

$$L_f = 0.0691(\mathrm{C/H} - 1.82)^{2.71}. \quad (21)$$

More recently Lefebvre [54] has proposed the following expression for L_f which is based on the hydrogen content of the fuel

$$L_f = 336/(\text{percentage } \mathrm{H}_2)^2. \quad (22)$$

Despite its obvious deficiencies equation (20) is still widely used for rough estimates of flame radiation in gas turbine combustors. However, its practical significance is somewhat dubious for combustors operating at high pressure, where the effects of atomization and fuel distribution on soot formation, and hence on gas radiation, are at least as important as variations in fuel type.

SOOT FORMATION THEORY

The processes governing the rates of formation and subsequent oxidation of soot are highly complex and quantitative models to describe these processes are not yet fully developed. However, the main controlling factors are much better understood.

For the pressures and temperatures prevailing in gas turbine combustors, equilibrium considerations suggest that solid carbon appears when there is insufficient oxygen to oxidize the fuel to CO and H_2. According to the reaction

$$\mathrm{C}_x\mathrm{H}_y + m\mathrm{O}_2 \rightarrow 2m\mathrm{CO} + \frac{y}{2}\mathrm{H}_2 + (x - 2m)\mathrm{C}_s \quad (23)$$

the formation of soot should start when x becomes equal to or larger than $2m$, i.e. when the C/O atomic ratio exceeds unity. However, since soot formation is essentially a non-equilibrium phenomenon, soot is observed at C/O ratios much less than unity for temperatures below 2000 K [55].

Soot formation models

As the exact routes by which soot is formed are poorly understood, quasi-global models have been developed to characterize the process of soot formation via a few overall steps. Such models have demonstrated good potential for predicting soot production rates [35, 56].

The quasi-global models cannot predict the size of soot particles. This is not a serious drawback since luminous emissivity is determined by the volume of soot present and is independent of particle size. Thus, for the purpose of analysis, it may be assumed that the soot particles are produced at a known size and a specified size distribution (e.g. Gaussian).

Tesner [57] proposed a model in which soot formation is assumed to occur in three rate-limited steps:

Pyrolysis

$$\dot{n} = aC_F \exp(-E/RT) \quad \text{part. m}^{-3}\,\text{s}^{-1}; \quad (24)$$

Nuclei formation

$$r_{f_n} = \dot{n} + (f - g)n - hNm \quad \text{part. m}^{-3}\,\text{s}^{-1}; \quad (25)$$

Soot formation

$$r_{f_s} = m(i - bN)n \quad \text{kg m}^{-3}\,\text{s}^{-1}; \quad (26)$$

where a, b, g, h, i, and E are constants for any given fuel, n is the nucleus concentration, $\dot{n}$ is the rate of spontaneous formation of nuclei, m is the mass of a soot particle, and N is the concentration of soot particles.

According to Khan and Greeves [58] the rate of soot production is determined by the partial pressure of unburned hydrocarbons, p_{UHC}, the equivalence ratio of the fresh mixture, ϕ, and the temperature, T. The effects of these parameters are combined into the single-step global expression

$$\mathrm{d}C_s/\mathrm{d}t = 0.468 p_{\mathrm{UHC}} \phi^3 \times \exp(-40\,000/RT)\,\text{g cm}^{-3}\,\text{s}^{-1}. \quad (27)$$

Soot oxidation rates are not considered in either of the above models.

Edelman and Harsha [59] have proposed the following modified Arrhenius type of relationship for soot formation

$$r_f = AT^a C_F^b C_{O_2}^c \exp(-E/RT)\,\text{g cm}^{-3}\,\text{s}^{-1} \quad (28)$$

where C_F and C_{O_2} are the concentrations of unburned fuel and oxygen, respectively, and A, E, a, b, and C, are model constants. The following equations are essentially those of Edelman and Harsha but the constants have been changed according to the recommendations of Najjar and Goodger [60]. These workers studied soot formation in a gas turbine combustor when burning kerosine, gas oil, or residual fuel. Their equations for kerosine and gas oil are:

Kerosine

$$\mathrm{d}C_f/\mathrm{d}t = 2 \times 10^6 P^{0.3} C_{O_2} C_F^{0.5} T \exp(-13\,600/T) \quad (29)$$

$$\mathrm{d}C_s/\mathrm{d}t = 4.4 \times 10^{14} C_F \exp(-12\ 100/T) - 3 \times 10^9 C_{O_2} \exp(-7800/T); \quad (30)$$

Gas oil

$$dC_f/dt = 2\times10^6 P^{0.3} C_F^{0.5} T \exp(-13\,800/T) \quad (31)$$

$$dC_s/dt = 4.4\times10^{14} C_F \exp(-11\,900/T) - 3\times10^9 C_{O_2} \exp(-7800/T); \quad (32)$$

where P is expressed in atm and species concentration in mol cm^{-3}.

Inspection of these equations reveals only marginal differences between kerosine and gas oil. As these two fuels represent fairly wide variations in C/H mass ratio (6.48–6.765) and aromatics (18.4–28.2) this might suggest that over the range of fuels of interest to aircraft gas turbines the rate of soot formation is about the same for all fuels. However, it is now well established that in gas turbines soot formation is influenced more by the physical processes of atomization, evaporation, and fuel/air/products mixing than by reaction kinetics.

Soot oxidation

The kinetics of soot oxidation are better understood than those of formation although there remains some doubt as to which species are most important. However, the properties of soots formed in flames appear to be remarkably similar, and little affected by the type of flame (i.e. premixed or diffusion) or the nature of the fuel [61].

The complete combustion of soot requires the presence of oxygen at temperatures above 1400 K. As higher temperatures prevail in the fuel-weak secondary zone and, in modern combustors, in the dilution zone also, a very large proportion of the soot formed in the primary zone is fully consumed in the regions downstream [62, 63].

Although attack by OH radicals in excess of their equilibrium concentration has been invoked to account for soot oxidation in fuel-rich, laminar, premixed flames it is generally agreed that in fuel-lean flames the dominant mode of soot depletion occurs via the heterogeneous reaction

$$C + 0.5\,O_2 = CO. \quad (33)$$

The following homogeneous reaction also contributes to the depletion of soot

$$CO + 0.5\,O_2 = CO_2 \quad (34)$$

via the reaction

$$C + CO_2 \rightleftarrows 2CO. \quad (35)$$

At low temperatures (< 1000 K) the rate of approach to equilibrium is slow and little soot is converted into carbon monoxide, whereas at temperatures higher than 1400 K the rate of conversion is fast. Thus in addition to C/O ratio, temperature is also important in determining the soot content of combustion products.

Soot oxidation models

The best-known model for the soot oxidation step is the semi-empirical formula of Nagle and Strickland-Constable [64] which is based on a theoretical model of the surface reaction mechanism proposed by Blyholder *et al.* [65]. This formula is nonlinear and non-Arrhenius in regard to p_{O_2} and temperature. The overall specific surface reaction is given by

$$w = 12[(\psi K_A p_{O_2})/(1 + K_Z p_{O_2}) + K_B p_{O_2}(1-\psi)] \text{ g cm}^{-2}\text{ s}^{-1} \quad (36)$$

where

$$\psi = (1 + K_T/p_{O_2}K_B)^{-1}, \quad K_A = 20 \exp(-30\,000/RT),$$

$$K_B = 4.46\times10^{-13} \exp(-15\,200/RT),$$

$$K_T = 1.51\times10^{-5} \exp(-97\,000/RT)$$

and

$$K_Z = 21.3 \exp(4100/RT).$$

Shock-tube measurements of soot oxidation rates confirm the general features of the above formula. Blazowski *et al.* [56] used equations (28) and (36) for soot formation and soot oxidation, respectively, assuming a constant soot particle size of 250 Å, to predict soot concentrations in close agreement with experimental data for a stirred reactor. However, these expressions assume perfect mixing, which is never achieved in gas turbine combustors.

Magnussen and coworkers [66, 67] have proposed a model that accounts for the effect of turbulent fluctuations on soot production rates. The main features of this model, along with equations (28) and (36), have been incorporated into a 3-D combustor performance program by Srinivasan *et al.* [35]. Preliminary computations indicate its ability to make qualitative predictions.

Najjar and Goodger [68] adopted the Nagle and Strickland-Constable equations, but they modified the constants to improve the prediction of smoke levels at the conditions of temperature and equivalence ratio found in the primary and secondary zones of gas turbine combustors.

For gas temperatures greater than 1800 K

$$K_A = 380 \exp(-12\,552/RT) \text{ g cm}^{-2}\text{ s}^{-1}\text{ atm}^{-1}$$

$$K_B = 4.46\times10^{-2} \times \exp(-63\,596.8/RT) \text{ g cm}^{-2}\text{ s}^{-1}\text{ atm}^{-1}$$

$$K_T = 1.15\times10^{5} \exp(-251\,040/RT) \text{ g cm}^{-2}\text{ s}^{-1}$$

$$K_Z = 5000 \exp(20\,920/RT) \text{ atm}^{-1}$$

where R is the universal gas constant (8.314 J mol^{-1} K^{-1}), and all the activation energies are in J mol^{-1}.

For gas temperatures less than 1800 K

$$K_A = 2300 \exp(-125\,520/RT) \text{ g cm}^{-2}\text{ s}^{-1}\text{ atm}^{-1}$$

$$K_Z = 2.13 \exp(17\,154.4/RT) \text{ atm}^{-1}.$$

Insertion of these values of K_A, K_B, K_T, and K_Z into equation (36) led to very satisfactory predictions of experimental data on exhaust smoke concentrations obtained over an operating range from idle to full power [68]. It is of interest to note that the maximum values of the soot-burning rate calculated by Najjar and Goodger are appreciably lower than estimates based on the methods of Lee *et al.* [69] and Fennimore and Jones [70]; also the soot-burning rate peaks at a much lower value of equivalence ratio.

In view of the marked differences exhibited by the various models currently available for the prediction of soot concentrations in combustion zones, it would seem most prudent to use the equations developed by Najjar and Goodger [60, 68]. Their approach has no fundamental advantage over other methods, but it does have the considerable merit which derives from the use of equations in which all the constants are based on the results of experiments carried out at representative gas turbine combustor conditions.

COMBUSTION CHAMBERS

Although a considerable amount of work has been done in measuring flame radiation and in assessing its susceptibility to various influences, the number of positive conclusions that can be drawn is relatively few, largely 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. These include the size and geometry of the combustion system, 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, plus a luminous component which is dependent upon the fuel employed, the fuel spray characteristics and the combustor operating conditions.

It is also well established that luminous radiation emanates from soot particles in the flame. Najjar and Goodger, for example, have demonstrated a strong correlation between exhaust smoke and radiation in the primary zone [71]. Claus [72] has also identified soot as the main contributor to flame radiation. His experiments on a JT8D can combustor showed that soot contributes typically from 70 to 80% of the total radiation in the primary zone, from 50 to 70% in the intermediate zone, and from 35 to 50% in the dilution zone.

In combustors fitted with pressure-swirl atomizers the main soot-forming region lies inside the fuel spray, at the center of the combustor. This is the region in which the recirculating burned products move upstream toward the fuel spray, and in which local pockets of fuel vapor are enveloped in oxygen-deficient gases at high temperature. In these high-temperature, fuel-rich regions, soot may be produced in considerable quantities by vapor-phase cracking.

Most of the soot produced in the primary zone is consumed in the high-temperature regions downstream [62, 63, 73]. Thus, from a smoke viewpoint, a combustor may be considered to comprise two separate zones—the primary zone, which governs the rate of soot formation, and the intermediate zone (and, on modern high-temperature engines, the dilution zone also), which determines the rate of soot consumption. The soot concentration actually observed in the exhaust gases is an indication of the dominance of one zone over the other.

For gas turbine combustors the main factors controlling soot formation and smoke have been determined experimentally to be fuel properties, combustion pressure and temperature, fuel/air ratio, atomization quality, and mode of fuel injection [62, 63, 74–86].

Fuel properties

Fuel properties can influence smoke production in two ways: first by inducing the formation of local overrich fuel 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 [19]. 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 which point the nonluminous component of radiation becomes dominant. Also, if the conversion to soot exceeds 3% the emissivity will be so close to unity that variations in fuel composition will have a negligible effect. For current combustor designs the efficiency for conversion to soot usually falls between these two extremes, so that fuel composition usually has 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 flames or laminar diffusion flames [57, 61, 70, 75, 77, 79, 87–94] and hence cannot be related directly to the conditions prevailing within gas turbine combustors [95, 96]. Nevertheless, it is reasonable to assume that the trends observed will provide an indication of actual fuel performance. These studies showed that the incipient sooting limit, i.e. the air/fuel ratio at which the flame just begins to produce soot, increases in the following manner:

paraffins < olefins < dicycloparaffins < benzenes < naphthalenes.

Little work has been reported concerning the sooting tendencies of turbulent diffusion flames, but Wright's studies on soot formation in a jet-stirred reactor [97, 98] 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 O/C ratios greater than unity, but the strong recirculation of burned products did afford some broadening of the soot-free O/C ratio.

Bowden and Pearson [95] used a model gas turbine combustor to study the influence of air/fuel ratio on the sooting tendencies of various hydrocarbons. Their results showed that the sooting tendencies of fuels containing only single-ring aromatics are related to the overall hydrogen content (or C/H ratio) of the fuel. However, experimental fuel blends containing high concentrations ($>20\%$ mass) of naphthalenes or tetralins exhibit sooting properties that are more dependent on the presence of such components than on the hydrogen content.

The important influence of hydrogen content on flame radiation was first demonstrated by Schirmer and coworkers [99, 100] who investigated a wide range of fuels at combustion pressures up to 1.5 MPa (15 atm). The results of their tests on the 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.* [101] and Humenik *et al.* [102] on much larger gas turbine combustors 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 composition on flame radiation [103]. They concluded that hydrocarbon molecular structure has at most a minor effect on flame radiation and that hydrogen content or C/H ratio is the main factor. They also noted that fuel viscosity and boiling point distribution have no significant effect on radiation even with end points as high as 675 K, which implies that the soot-forming reactions are gas-phase rather than liquid-phase pyrolysis. In subsequent studies, by suitable blending Naegeli and coworkers [104, 105] were able to produce fuels of constant hydrogen content and varying aromatics content. These blended fuels allowed them to study the separate effects on flame radiation of C/H ratio and percentage aromatics. Their results showed that the dominant soot formation mechanisms in gas turbine engines are dependent on combustor operating conditions. There appears to be a number of competing soot formation and oxidation steps whose relative importance varies with inlet air temperature, reference velocity, and fuel/air ratio. Naegeli *et al.* also found that under some operating conditions the sooting tendency is affected significantly by polycyclic aromatics, but the C/H ratio is the principal correlating parameter. Figure 4 shows what was typically observed for the effect of polycyclic aromatic ring carbon on flame radiation. It is apparent in this figure that flame radiation has a linear dependence on polycyclic aromatics content.

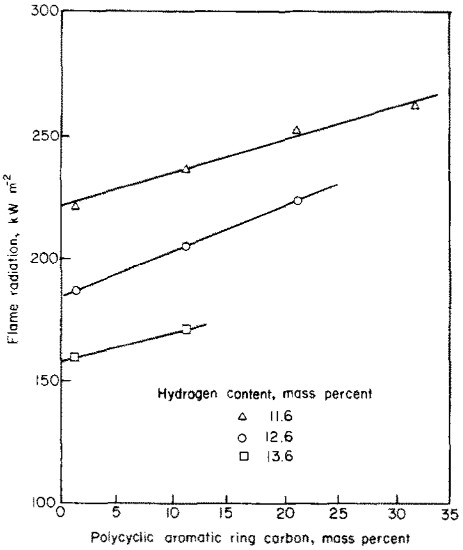

FIG. 4. Effects of hydrogen content and polycyclic aromatic ring carbon on flame radiation intensity [105].

According to Clark [106] an appropriate correlation parameter for these data would be

$$[\%H_2 - 0.055(\%PA)].$$

However, Clark has proposed an alternative fitting parameter having a nonlinear dependence on polycyclic aromaticity of the form

$$[\%H_2 - (\%PA)^n]$$

where $0.1 \leqslant n \leqslant 0.4$.

The advantage claimed for this parameter is that it provides an excellent fit to the radiative flux data obtained both by Naegeli *et al.* [105] and by Clark [106]. As both expressions appear to be equally valid over the range of existing data, more radiation flux data from fuels whose polycyclic aromatics content is either very low or very high are needed to determine which fitting parameter is best.

Available evidence on the influence of fuel type on flame radiation in industrial gas turbine combustors generally confirms the results obtained with aircraft combustion chambers. The work of Hunyadi and Anderson [107], for example, has shown that changing the fuel from natural gas to heating oil and then to heavy distillate fuel produces a progressive increase in radiant heat flux to the liner wall. Figures 5 and 6 are typical of the results obtained.

Air-inlet temperature

All the available evidence suggests that flame radiation increases markedly with rise in air-inlet temperature, although the relative magnitude of the contributions made by emissivity and flame temperature to this increase is not yet clear. The most important factor governing emissivity at high pressures is the soot concentration. Millikan showed that soot formation in premixed flames decreases as the flame temperature is

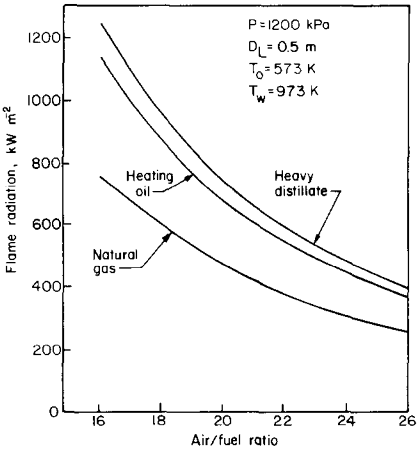

FIG. 5. Heat flux to liner walls as a function of fuel type and air/fuel ratio [107].

increased [108]. This was attributed to increased oxidation of soot particles by OH radicals in the flame. In contrast Glassman and Yaccarino [109] showed that the sooting tendency of diffusion flames increased with an increase in flame temperature. Measurements of flame opacity and flame temperature in the Phillips 5 cm combustor led Naegeli *et al.* to conclude that fuel pyrolysis is a dominant process in the formation of soot in turbulent diffusion flames [110]. These pyrolytic reactions would be expected to be temperature sensitive, being controlled by chemical kinetics.

In the primary zone of a gas turbine combustor the effect of an increase in inlet air temperature could be either to increase or decrease soot formation, depending on the local fuel/air ratio. If the burning zone is fuel-rich an increase in temperature will accelerate the pyrolitic reactions and thereby produce more soot. However, if ample air is available and mixing rates are adequate, the soot oxidation reactions will be enhanced, leading to lower soot concentrations. Downstream of the main combustion zone, where equivalence ratios are usually well below unity, an increase in air-inlet temperature tends to lower both the nonluminous and luminous components of emissivity, the latter by promoting the rate of soot oxidation. However, regardless of its influence on emissivity, the effect of an increase in air-inlet temperature is always to increase flame radiation, as shown in Fig. 7. This, of course, is due to the Stefan–Boltzmann 4th power relationship between radiation and temperature.

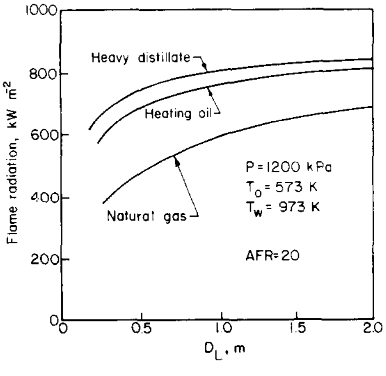

FIG. 6. Influence of liner diameter and fuel type on heat flux to liner wall [107].

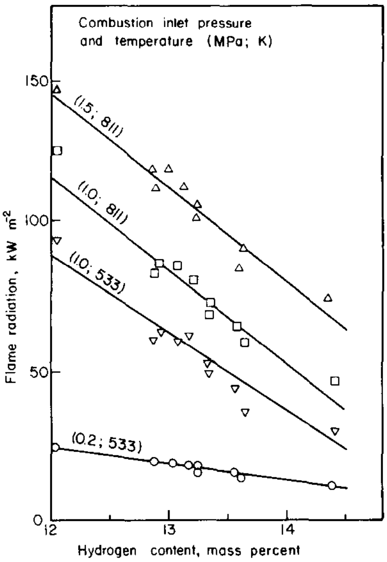

FIG. 7. Effect of combustor operating conditions and fuel hydrogen content on flame radiation [103].

Pressure

Problems due to flame radiation are most severe at high pressures. There are several reasons for this, some of which derive from chemical effects, while others stem from physical factors which affect spray characteristics and hence the distribution of mixture strength in the soot-generating regions of the flame [76–81]. For premixed kerosine–air flames it is found that no soot is formed at pressures below around 0.6 MPa, or at equivalence ratios below about 1.3 [79]. One adverse effect of an increase in pressure is to extend the limits of flammability, so that soot is produced in regions which, at lower pressures, would be too rich to burn. Increases in pressure also accelerate chemical reaction rates, so that combustion is initiated earlier and a larger proportion of the fuel is burned in the fuel-rich regions adjacent to the atomizer.

With pressure atomizers of the duplex or dual-orifice type, the main factor contributing to high flame radiation at high pressures is the influence of pressure on the characteristics of the fuel spray. An increase in gas pressure produces an increased resistance to the movement of individual fuel drops and, at the same time, a reduction in mean drop diameter. The net effect is to increase the surface-to-volume ratio of the spray so that both the rate of evaporation and the drag of the spray are increased. These two effects are cumulative in reducing the penetration of the spray. Thus, instead of the fuel distributing itself evenly across the primary

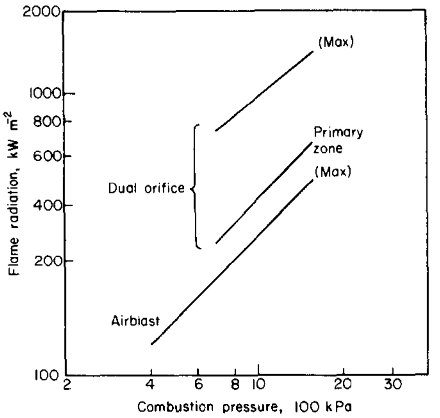

FIG. 8. Influence of fuel injection method on maximum flame radiation [52].

zone, at high pressures it tends to concentrate at the center of the liner in the vicinity of the spray nozzle. This local fuel-rich zone, surrounded by oxygen-deficient gases, constitutes ideal conditions for the production of soot. Airblast atomizers are spared these problems because the fuel drops they produce are always airborne and their distribution throughout the combustion zone is dictated solely by the liner airflow pattern which is not susceptible to changes in pressure.

Another mechanism by which flame radiation is enhanced at high pressures stems from the effect of pressure in suppressing chemical dissociation which results in higher combustion temperatures. Although the increase in temperature is not large, its effect on radiation, which is proportional to T^4, can be significant.

All reported studies on the effect of pressure show that flame radiation increases markedly with an increase in combustion pressure [49–52, 96, 99, 103, 111]. The results shown in Figs. 7 and 8 are typical of those obtained in all investigations. However, if the pressure is raised continually the soot concentration will eventually reach a level such that blackbody radiation is approached so that additional soot will have little or no effect. Measurements to support this view have been reported by Marsland *et al.* [49] and Najjar and Goodger [71]. A further increase in pressure beyond this critical value will tend to reduce liner wall temperatures by increasing the convective heat transfer between the liner and its cooling air.

Velocity

Since, for reasons of size and pressure loss, most combustors are designed within a fairly small range of reference velocities, the influence of velocity on radiation has no great practical significance.

The effect of a change in velocity on radiation depends upon how the change is brought about. For any given combustor, operating at constant pressure and overall air/fuel ratio, an increase in velocity is accompanied by a corresponding increase in fuel flow and a rise in fuel pressure. The increase in fuel flow tends to raise the soot concentration but, for pressure atomizers, the rise in fuel pressure, by improving the atomization quality, tends to reduce it. The net result is that the influence of velocity is usually quite small. In general, an increase in velocity leads to a reduction in radiation intensity [52, 100, 103].

However, if the change in velocity is accomplished by a modification to the combustor flow area, with the fuel and airflows kept constant, then the influence of velocity is more pronounced. The effect of an increase in velocity is to raise the turbulence level in the combustion zone and probably also the proportion of the total airflow that is entrained into the recirculation zone. Both effects lead to improved mixing and aeration of the soot-forming regions in the flame and, hence, to reductions in emissivity and radiation.

Fuel/air ratio

Holderness and Macfarlane [79] have shown for premixed kerosine/air mixtures that no carbon is formed at equivalence ratios less than 1.3. Thus all that is needed to eliminate soot is to ensure that nowhere in the flame region is this equivalence ratio exceeded. However, even when the overall equivalence ratio in the primary zone is well below 1.3, imperfections in fuel–air mixing can create local regions in which pockets of fuel-rich mixture are enveloped in oxygen-deficient gases at high temperature, leading to high rates of soot formation. The superior performance of the airblast atomizer is due partly to better atomization but also to the thorough fuel–air mixing incurred in the atomization process prior to combustion, which effectively eliminates fuel-rich pockets from the combustion zone.

In general, any decrease in fuel flow rate automatically lowers the fuel concentration in the reaction zone, thereby reducing the rate of soot formation and hence the flame emissivity. At the same time the combustion temperature falls, so that the net effect is a significant reduction in flame radiation. This is shown in Fig. 5 for a large industrial-type chamber, and also in Fig. 9 in which the three curves correspond to three different values of the air/fuel ratio. For each air/fuel ratio the level of radiation increases to a

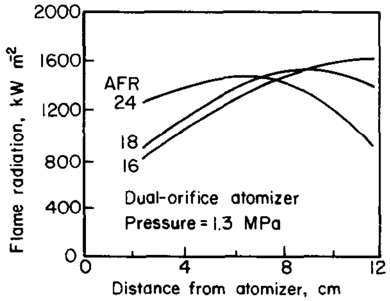

FIG. 9. Influence of overall fuel/air ratio and downstream distance on flame radiation [52].

maximum value with downstream distance, and then starts to decline. Increased fuel flow causes the peak to occur further downstream. The practical significance of these results lies in the fact that problems of liner overheating tend to occur at the two extreme operating values of air/fuel ratio. At high air/fuel ratios (corresponding to engine idle conditions), radiation levels attain their highest values near the dome or flare. An increase in fuel flow reduces the radiation in the dome region and produces higher levels further downstream. Maximum radiation is obtained at the highest fuel flow and occurs just downstream of the primary combustion zone. Thus, at low power settings, overheating of the dome is the most serious problem, while at full power the radiant heat flux to the wall is most severe in the intermediate zone.

Fuel spray characteristics

According to Sjorgren [112], an important factor affecting soot formation is the relative velocity between the droplets in the fuel spray and the combustion air. As the fuel spray approaches the flame zone, heat transmitted from the flame starts to evaporate the droplets. The smaller droplets in the spray have enough time to evaporate completely ahead of the flame front, and the fuel vapors then mix with the combustion air and burn essentially as a premixed flame. However, the larger droplets in the spray do not have sufficient time to evaporate completely, and they burn as individual droplets, each of which is surrounded by a diffusion flame. With a premixed flame, soot formation does not occur until the amount of available air is reduced to around 75% of the stoichiometric value. However, for the diffusion flame surrounding a droplet, soot formation is dependent only on the fuel and the size of the drop. Thus an increase in air/fuel ratio can have little or no effect on soot formation.

In these circumstances it is advantageous to try to extinguish the flame, either by increasing the relative velocity between the droplet and the surrounding air, or by changing the composition of the air so that the flame around the droplet either goes out or becomes a premixed nonsooting flame in the wake of the droplet. Extinction occurs when the relative velocity between the droplet and the surrounding air exceeds a certain critical velocity. This critical velocity depends on the droplet size and the composition of the combustion gases. The extinction velocity increases in proportion to the square root of the drop diameter and falls off considerably with a decrease in oxygen concentration. So, the beneficial effect of exhaust-gas recirculation in curbing soot formation may be due in part to a lower extinction velocity caused by a reduction in the oxygen concentration of the combustion gases.

The above discussion highlights fuel drop size as a key factor affecting soot formation and flame radiation. It follows therefore that a main objective of fuel nozzle design should be to ensure minimum drop sizes at the combustor operating conditions where excessive flame radiation could lead to serious overheating of the liner. Unfortunately, as mentioned earlier, with pressure-swirl atomizers any improvement in atomization quality reduces the penetration of the fuel spray and leads to the formation of fuel-rich, soot-forming zones adjacent to the fuel nozzle. Thus the lower levels of soot and flame radiation that are generally associated with airblast atomizers (see, for example, Fig. 8) are due in no small measure to the thorough fuel/air mixing incurred during atomization which effectively eliminates fuel-rich pockets from the combustion zone.

Combustor size

An increase in liner size should increase gas radiation owing to the longer beam length, the actual extent of this increase being greater for lower initial values of emissivity. Figure 6 shows experimental data on this effect, obtained by Hunyadi and Anderson [107]. For a heavy distillate fuel it was found that a fourfold increase in liner diameter produced a 20% increase in radiant heat transfer.

Combustor design

In combustion chambers fitted with spray atomizers, the main soot-forming region lies at the center of the primary zone inside the fuel spray. Thus, any modification to either the fuel injector or liner that reduces the concentration of fuel in this region will effectively reduce soot formation and hence, also flame emissivity [76].

In the design of the liner, care should be taken to ensure that the maximum possible amount of air participates in primary-zone recirculation, consistent with adequate relighting capability at altitude. Ideally, the primary zone should be no richer than stoichiometric and preferably much weaker. It is, of course, important that the primary-zone air should have sufficient penetration to reach the soot-forming zone at the center of the liner. This penetration is determined mainly by the size of the primary air holes and the pressure drop across them. A high-pressure drop is particularly useful because it assists both in the penetration of the air jets and also, by raising the turbulence level, in their subsequent mixing with fuel and combustion products.

In general, any modifications that lead to better premixing of air and fuel prior to combustion, such as occurs in the airblast atomizer, or which attempt to achieve complete evaporation of the fuel and complete mixing of fuel and air prior to combustion, as in the NASA lean premix–prevaporize combustor [113, 114] will reduce luminous flame radiation and will also make flame radiation much less susceptible to variations in fuel composition.

SUMMARY OF MAIN POINTS

All experimental observations on the influence of design factors and operating variables on flame radiation in gas-turbine combustors are consistent with the view that luminous radiation emanates from soot particles produced in the high-temperature, fuel-rich regions of the combustion zone. For light and middle distillate fuels this soot formation is due primarily to gas phase reactions. Any change that increases the temperature and fuel/air ratio in these regions will accelerate the rate of soot formation and thereby increase flame radiation. Most of the soot produced in the primary zone is consumed in the high-temperature, oxygen-rich regions downstream. Thus the soot concentration actually observed in the exhaust gases is an indication of the relative importance of the competing soot formation and soot oxidation processes.

Flame radiation increases with increase in combustion pressure. This is due partly to increased soot formation but also to the effect of pressure in suppressing chemical dissociation which raises the temperature of the radiating gases and soot particles. Change in inlet-air temperature may raise or lower the emissivity, depending on the fuel/air ratio. Provided sufficient oxygen is available an increase in inlet-air temperature will generally lower soot concentrations due to the enhancement of soot oxidation rates. However, although both the nonluminous and luminous components of emissivity are usually diminished by elevation of inlet-air temperature, the flame radiation will almost certainly increase due to the fourth power relationship between total radiation and temperature.

All the available evidence indicates that flame radiation decreases with increase in combustor reference velocity, but to what extent this is due to the elimination of fuel-rich pockets by better mixing, or to improved atomization is not clear.

The most satisfactory way of minimizing radiation lies in the design of the liner and fuel injector. In particular the primary zone should be designed for the lowest feasible equivalence ratio, with the air supplied in the form of highly turbulent jets of sufficient penetration to reach potential soot-forming zones. Not the least advantage of a fuel weak primary zone is that, by reducing the contribution made by radiation to the liner walls, wall temperatures become less sensitive to variations in fuel composition. Further fuel flexibility is obtained with fuel injectors that provide some measure of fuel–air mixing prior to atomization, such as the airblast atomizer.

Fuel composition is unimportant at low pressures where nonluminous radiation predominates, and also at high pressures where the flame emissivity is close to unity for all fuels regardless of composition. However, within the pressure range of interest for gas turbines—i.e. between about 0.5 and 2.5 MPa (5–25 atm)—flame radiation is very dependent on fuel type and composition. The results of recent studies show that hydrogen content, or C/H ratio, is the principal correlating parameter for sooting tendency and flame emissivity, while the effect of polycyclic aromatics is seen as perturbation of this correlation. It is also observed that the effect of fuel type on flame radiation is quite sensitive to combustor operating conditions.

The manner in which flame radiation varies along the liner length is very dependent on the mode of fuel injection. In combustors fitted with pressure-swirl atomizers flame radiation increases with increasing distance downstream of the fuel injector until a peak is reached, beyond which it declines due to soot oxidation. Increase in fuel flow rate causes the peak to occur further downstream. Thus, at low power settings, overheating of the dome is the most serious problem, while at full-power operation the radiant heat flux to the liner wall is most severe in the intermediate zone. With airblast atomizers flame radiation attains its maximum value fairly close to the fuel injector and then slowly diminishes with increase in downstream distance.

At the present time, the situation in regard to flame radiation in gas turbines is satisfactory only to the extent that the influences of fuel composition and the operating variables of pressure, temperature, velocity, and air/fuel ratio are known qualitatively, and design rules for achieving minimum radiation have been established. Undoubtedly the major cause for concern is the lack of a reliable method of predicting the soot concentrations and hence the emissivities of luminous flames at high pressures. This is a serious weakness, since it is at high pressures, where a small increase in radiant energy can drastically reduce liner life, that accurate estimates of radiation intensity are most needed. With the advances now being made in analytical methods and modeling techniques, the lack of a satisfactory quantitative basis for linking the emissivity of a luminous flame to the size and geometry of the combustion chamber, the chemical and physical properties of the fuel, the fuel spray characteristics, and the pressure, temperature, turbulence, and fuel/air ratio of the flame zone, remains a serious impediment to the prediction of flame radiation and liner wall temperatures.

Acknowledgement—The author wishes to thank his colleague Professor Ray Viskanta for his useful comments and suggestions on this paper.

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RADIATION DE FLAMME DANS LES CHAMBRES DE COMBUSTION DES TURBINES A GAZ

Résumé—Une rapide description de la nature du rayonnement de flamme dans les chambres de combustion de turbine à gaz est suivie d'une discussion des méthodes et des modèles disponibles pour estimer l'émissivité des gaz lumineux ou non. Puisque le rayonnement lumineux émane des particules de suie dans la flamme, on considère les mécanismes de formation de la suie et de l'oxydation de la suie, et l'influence de la composition chimique sur la tendance des combustibles à former de la suie. Des expériences pour l'effet sur le rayonnement de flamme des variations de pression, température, vitesse et rapport combustible/air permettant une discussion. On considère aussi l'importance sur le rayonnement des propriétés du combustible et des caractéristiques de la pulvérisation.

FLAMMENSTRAHLUNG IN BRENNKAMMERN VON GASTURBINEN

Zusammenfassung—Ausgehend von einer kurzen Beschreibung der Flammenstrahlung in Gasturbinenbrennkammern werden die vorhandenen Methoden und Modelle zur Bestimmung des Strahlungsvermögens im nicht sichtbaren und im sichtbaren Bereich erörtert. Da sichtbare Strahlung durch Rußpartikel in der Flamme verursacht wird, werden Überlegungen über die Vorgänge der Rußbildung und Rußoxidation sowie über den Einfluß der chemischen Zusammensetzung von Brennstoffen auf die Neigung zur Bildung von Ruß angestellt. Anhand von Meßdaten wird der Einfluß veränderlicher Betriebsbedingungen in der Brennkammer (Druck, Temperatur, Geschwindigkeit und Brennstoff/Luft-Verhältnis) auf die Flammenstrahlung diskutiert. Ebenso werden die wichtigsten Einflüsse der Brennstoffeigenschaften und Brennstoffzerstäubungscharakteristik auf die Flammenstrahlung in Betracht gezogen.

ИЗЛУЧЕНИЕ ПЛАМЕНИ В ТОПОЧНЫХ КАМЕРАХ ГАЗОВЫХ ТУРБИН

Аннотация—Дано краткое описание характера излучения пламени в топках газовых турбин, а затем рассмотрены методы и модели, которые используются для оценки излучательной способности несветящейся и светящейся сред. Поскольку вторая состоит из частиц сажи, находящихся в пламени, рассмотрены процессы их образования и окисления, а также влияние химического состава топлива на тенденцию к сажеобразованию. Проведено обсуждение экспериментальных данных по влиянию на излучение пламени изменений рабочего режима топки, давления, температуры, скорости и отношения между количеством топлива и воздуха. Также рассмотрено существенное влияние на излучение пламени свойств топлива и его аэрозольных характеристик.