Measurement of Surface Temperatures and Spectral Emissivities During Laser Irradiation

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Observations with a four-band radiometer of the spectral radiance temperatures of a carbon-phenolic sample are used to determine the front-face temperature and spectral emissivities (0.53, 1.06, 3.8, and 7.8 μm) on the sample when subjected to cw laser irradiation (10.6 μm). A spectral method is employed that assumes a value for the shortest wavelength spectral emissivity value and is compared to the classical ratio method. Error analysis for each of the methods is presented along with discussion on multispectral methods that may be useful for certain situations.

Nomenclature

c_{L1} = first radiation constant, 1.191062×10^8 W · μm^4 · m^{-2} · sr^{-1}
c_2 = second radiation constant, 1.438786×10^4 μm · K
L_λ = spectral radiance, W · m^{-2} · sr^{-1}
S = signal, V or μA
T = temperature, K
T_r = ratio temperature, K
T_λ = spectral radiance temperature, K
ϵ_λ = spectral emissivity
λ = wavelength, μm
Λ = equivalent wavelength, μm

Subscripts

b = blackbody conditions
i = spectral bandpass
r = ratio method condition

Introduction

KNOWLEDGE of the front-face surface temperature during a laser-surface interaction is important for understanding the behavior of the material and the nature of the thermal processes that are occurring at the surface. The thermal radiative processes, including absorption of the laser irradiation and emission from the surface, are significant in the energy analysis for predicting the temperature/time history of the surface. For this reason it is desirable to know the spectral absorptivity at the laser wavelength. Radiometric methods have been used successfully for measuring surface temperatures but, under conditions where the target emissivity is known, can be readily estimated or at least remains constant during the observation period.

In the present application, a target material is irradiated by a laser source causing the surface to rapidly heat up and reach a quasisteady temperature under ablative conditions. A four-band radiometer,[1,2] with bandpasses centered at 0.53, 1.06, 3.8, and 7.8 μm (the first three are narrow bands, <2% of the center wavelength, whereas the last has a half-width of 0.45 μm), has been used to determine the surface temperature according to the following scheme. The radiometer provides measures of the spectral radiance temperatures ($T_{\lambda 1}$, $T_{\lambda 2}$, $T_{\lambda 3}$, $T_{\lambda 4}$) corresponding to the four bandpasses centered at λ_1, λ_2, λ_3, and λ_4. The true temperature T of the target material is determined using Wien's law with an *assumed* value of the target spectral emissivity at the shortest wavelength $\epsilon_{\lambda 1}$ and the corresponding spectral radiance temperature $T_{\lambda 1}$. Using this calculated or *inferred* value for the target true temperature, Wien's (or if more appropriate, Planck's) law is used with the other spectral radiance temperatures to calculate the spectral emissivities for the longer wavelength conditions, $\epsilon_{\lambda 2}$, $\epsilon_{\lambda 3}$, and $\epsilon_{\lambda 4}$.

The objectives of the present study are to evaluate the method by reviewing its derivations and assumptions; to review other radiation thermometry techniques that may have attractive features for modification or extension of the method; and to perform an analysis of test data on a carbon-phenolic material for the purpose of establishing confidence in the calculated temperature and spectral emissivity results.

Spectral Method

Principle of the Method

The four-band spectral (λ_1, λ_2, λ_3, λ_4) radiometer[1,2] is calibrated to indicate correctly the temperature of a blackbody from measured spectral radiances. The temperature of the surface viewed by the radiometer is inferred from the measured spectral radiance temperature $T_{\lambda 1}$ at the shortest wavelength λ_1 with the temperature equation[3]

$$\frac{1}{T} = \frac{1}{T_{\lambda 1}} + \frac{\lambda_1}{c_2} \ell n \, \epsilon_{\lambda 1} \tag{1}$$

using Wien's law for blackbody spectral radiance and an assumed value for the spectral emissivity. The relative uncertainty in the inferred true temperature owing to the relative uncertainty in the estimated emissivity is

$$\frac{\Delta T}{T} = \frac{\lambda_1 T}{c_2} \frac{\Delta \epsilon_{\lambda 1}}{\epsilon_{\lambda 1}} \tag{2}$$

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For most practical test situations, $\lambda_1 T \ll c_2$ because λ_1 corresponds to the short wavelength (0.53 μm) and the surface temperatures are high ($T > 1500$ K). Hence, the error in the inferred temperature caused by the uncertainty estimate in the assumed emissivity may be acceptable. For the prescribed spectral and temperature conditions (1500 K, 0.53 μm), a 10% emissivity uncertainty will result in a 0.5% temperature error.

Having determined the true surface temperature, the temperature equation using Planck's law, which is more appropriate for larger values of λT, can be employed to calculate the spectral emissivities for the longer wavelength conditions (λ_2, λ_3, λ_4),

$$\epsilon_{\lambda i} = \frac{\exp(c_2/\lambda_i T) - 1}{\exp(c_2/\lambda_i T_{\lambda i}) - 1} \tag{3}$$

where $T_{\lambda i}$ are the measured spectral radiance temperatures for $i = 2,3,4$. Equation (3) can be differentiated to obtain an error equation in terms of the assumed uncertainty in the estimated emissivity for the shortest wavelength $\Delta\epsilon_1$, i.e.,

$$\frac{\Delta\epsilon_{\lambda i}}{\epsilon_{\lambda i}} = \frac{1 - \exp(-c_2/\lambda_1 T)}{1 - \exp(-c_2/\lambda_i T)} \cdot \frac{\lambda_1}{\lambda_i} \cdot \frac{\Delta\epsilon_1}{\epsilon_1} \tag{4}$$

In its simplest form, where the exponential terms are small, the relative error for the calculated emissivities is the fraction λ_1/λ_i of the relative error for the assumed emissivity. For the present example ($T = 1500$ K), with an uncertainty for the assumed emissivity value $\epsilon_{\lambda 1}$ of 10%, the relative errors for the three spectral conditions (1.06, 3.8, and 7.8 μm) are 5.0, 1.4, and 1.0%, respectively, as can be seen from Fig. 1. For many applications, these levels of precision for the radiative properties may be quite acceptable.

Implementation of the Spectral Method

The method, as implemented by the four-band radiometer, involves the following steps: 1) assume a value of the spectral emissivity at the shortest wavelength $\epsilon_{\lambda 1}$ and identify the uncertainty limits $\Delta\epsilon_{\lambda 1}$; 2) use the temperature measurement equation, Eq. (1), to calculate the target true temperature from the measured spectral radiance temperature $T_{\lambda 1}$ and the assumed value for the spectral emissivity $\epsilon_{\lambda 1}$; 3) use the rearranged form of the temperature measurement equation, Eq. (3), to calculate the spectral emissivities $\epsilon_{\lambda 2}$, $\epsilon_{\lambda 3}$, $\epsilon_{\lambda 4}$ from the measured spectral radiance temperatures $T_{\lambda 2}$, $T_{\lambda 3}$, $T_{\lambda 4}$, and the true target temperature calculated in the previous step; and 4) use the uncertainty relationship, Eq. (4), to determine the relative error for the spectral emissivities calculated in the previous step due to uncertainty in the estimate for the assumed value of $\epsilon_{\lambda 1}$.

Relative Errors and Wavelength Selection

The most striking feature of the method is that the relative errors are much less, by a factor of λ_1/λ_i approximately, than the relative uncertainty of the assumed spectral emissivity $\epsilon_{\lambda 1}$. This feature has long been recognized in radiation thermometry practice for the selection of spectral bandpasses. The effect of emissivity uncertainty for a spectral radiation thermometer is less at shorter wavelengths. It is also important to recognize that errors resulting from the noise-to-signal ratio $\Delta S/S$ propagate in the same fashion as do those of the emissivity uncertainties

$$\frac{\Delta T}{T} = \frac{\lambda T}{c_2}\left(\frac{\Delta\epsilon_\lambda}{\epsilon_\lambda} + \frac{\Delta S}{S}\right) \tag{5}$$

This effect will be considered in the subsequent discussion of other methods.

This general approach was used in 1973 for measuring surface temperatures of reusable surface insulation (RSI) materials subjected to a convection heating environment.[4,5] With target temperatures near 1600 K for those experiments, emissivity uncertainty effects were acceptably small when using a spectral optical pyrometer operating at 0.40 μm. Referring now to Eq. (2), note that for this situation $\lambda T/c_2 = 1/22$, and indeed the effect of the emissivity uncertainty on the temperature error is quite small. For the four-band radiometer and typical temperatures near 2600 K, $\lambda_1 T/c_2 = 1/10$. If the radiometer could have been operated at 0.4 μm, the value of $c_2/\lambda T$ and hence the effect of estimated emissivity uncertainty could have been reduced by approximately 30%.

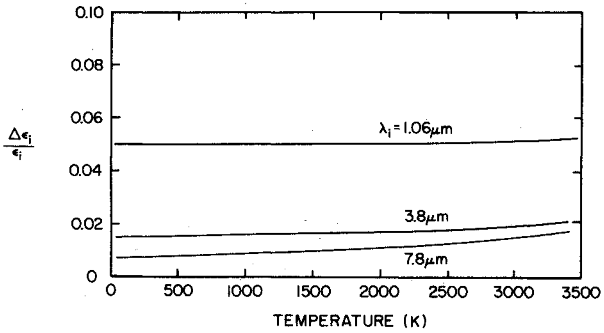

Fig. 1 Relative error of the spectral emissivity $\Delta\epsilon_{\lambda i}/\epsilon_{\lambda i}$ at wavelengths λ_i ($i = 2,3,4$) owing to the relative uncertainty of the spectral emissivity at $\lambda_1 = 0.53$ μm as a function of temperature for $\Delta\epsilon_{\lambda 1}/\epsilon_{\lambda 1} = 0.10$.

Ratio Method

Principle of the Method

The *ratio* (dual-wavelength or two-color) method provides for inferring temperature of the surface from the measured ratio of the spectral radiances at two wavelengths (narrow spectral bandpasses) and knowledge of the spectral emissivity ratio. The temperature measurement equation is obtained by extending the derivation used for the spectral method

$$\frac{1}{T} = \frac{1}{T_{\lambda i}} + \frac{\lambda_i}{c_2} \ell n\, \epsilon_{\lambda i} \tag{6}$$

where $i = 1,2$. By combining these two relations, find that

$$\frac{1}{T} = \frac{\Lambda}{\lambda_1 T_{\lambda 1}} + \frac{\Lambda}{\lambda_2 T_{\lambda 2}} \tag{7}$$

where $T_{\lambda 1}$ and $T_{\lambda 2}$ are the spectral radiance temperatures; the equivalent wavelength Λ is

$$\Lambda = \lambda_1 \lambda_2 / (\lambda_2 - \lambda_1) \tag{8}$$

for the condition where $\lambda_2 > \lambda_1$, and the emissivity ratio is

$$\epsilon_r = \epsilon_1 / \epsilon_2 \tag{9}$$

The first two terms on the right-hand side of Eq. (7) may be combined as

$$\frac{1}{T_r} = \Lambda\left(\frac{1}{\lambda_1 T_{\lambda 1}} + \frac{1}{\lambda_s T_{\lambda 2}}\right) \tag{10}$$

such that the temperature measurement equation has the simple form

$$\frac{1}{T} = \frac{1}{T_r} + \frac{\Lambda}{c_2} \ell n\, \epsilon_r \tag{11}$$

The ratio temperature T_r is the temperature of an equivalent blackbody having the same ratio of spectral radiances at two specified wavelengths as that of the target.

The primary advantage of the ratio method is now evident. For a gray body with $\epsilon_{\lambda 1} = \epsilon_{\lambda 2}$ or $\epsilon_r = 1$, the indicated ratio temperature of the radiometer is the true temperature.

Effects of Emissivity Uncertainty and Noise

From the simplified temperature measurement equation, Eq. (11), the effect of the emissivity ratio uncertainty on inferred temperature is evident. By differentiation, find that

$$\frac{\Delta T}{T} = \frac{\Lambda T}{c_2} \frac{\Delta \epsilon_r}{\epsilon_r} \tag{12}$$

Note the similarity of form between Eq. (12) and the error equation for the spectral method, Eq. (2). The differences in the parameters (Λ and λ_1) and (ϵ_λ and ϵ_r) are substantial, however. The equivalent wavelength can be many times greater than λ_1 or λ_2, thereby increasing the relative error in temperature because of uncertainty in the emissivity for the ratio method over the spectral method. However, the emissivity uncertainty is that of the ratio ϵ_1/ϵ_2 and not ϵ_1 or ϵ_2 separately. With λ_1 and λ_2 closely spaced, it is unlikely that $\Delta\epsilon_r/\epsilon_r$ will range much beyond ± 0.10 for most materials.

From the measurement equation, it can be shown that the effect of noise-to-signal ratio on temperature uncertainty will have the form

$$\frac{\Delta T}{T} = \frac{\Lambda T}{c_2}\left(\frac{\Delta \epsilon_r}{\epsilon_r} + \frac{\Delta S_r}{S_r}\right) \tag{13}$$

where S_r is the ratio of the signals proportional to the spectral radiances (S_1/S_2) and ΔS_r the uncertainty of this ratio. Since Λ in general will be much larger than λ_1 or λ_2, the ratio method is more adversely affected by noise-to-signal ratio than the spectral method.

Implementation of the Ratio Method

Using λ_1 and λ_2 (0.53 and 1.06 μm) as the spectral bandpasses, Eq. (7) is used to calculate the true temperature from measured spectral radiance temperatures $T_{\lambda 1}$ and $T_{\lambda 2}$ and an assumed (estimated) value for the emissivity ratio. The uncertainty in the calculated temperature is determined from Eq. (12) using an estimate for the emissivity ratio uncertainty.

The spectral emissivities at λ_3 and λ_4 are determined from Eq. (3) using the calculated true temperature and the spectral radiance temperatures $T_{\lambda i}(i = 3{,}4)$. The uncertainties in $\epsilon_{\lambda i}(i = 3{,}4)$ are then estimated from the following expression, which is similar in form to Eq. (4):

$$\frac{\Delta \epsilon_i}{\epsilon_i} = \frac{1-\exp(-c_2/\Lambda T)}{1-\exp(-c_2/\lambda_i T)} \cdot \frac{\Lambda}{\lambda_i} \cdot \frac{\Delta \epsilon_r}{\epsilon_r} \tag{14}$$

Note again the influence of the equivalent wavelength Λ. For $\lambda_1 = 0.53$ μm and $\lambda_2 = 1.06$ μm, the value of the equivalent wavelength is $\Lambda = 1.06$ μm. Since $\lambda_3 = 3.8$ μm and $\lambda_4 = 7.8$ μm, it follows that $\Lambda \ll \lambda_3$ or λ_4, and a favorable situation occurs wherein $\Delta\epsilon_i/\epsilon_i(i = 3{,}4)$ will be a fraction of $\Delta\epsilon_r/\epsilon_r$.

Comparison of the Spectral and Ratio Methods

An objective of our analysis is to compare the sensitivities of the spectral and ratio methods to uncertainties in emissivity. The spectral method is less sensitive to emissivity (and signal noise) uncertainties as can be readily seen by comparing Eq. (2) for the spectral method with Eq. (12) for the ratio method.

Two features need to be carefully recognized. First, it is evident that for the ratio method, the equivalent wavelength Λ defined in Eq. (8) always will be equal to or larger than either λ_1 or λ_2. Hence, the important parameter $\Lambda T/c_2$ for the ratio method usually will be larger than the parameter $\lambda T/c_2$ for the spectral method. Second, for the spectral method, the relative uncertainty of the emissivity is of interest; for the ratio method, the relative uncertainty of the emissivity ratio ϵ_r is of interest. In most situations, the former will be substantially larger than the latter.

The outcome of the comparison is not decisive, for a tradeoff between wavelength and emissivity factors is possible. The influence of the wavelength selection for the ratio method is illustrated in Fig. 2 and helps to make the case for using the ratio method in the present application. Consider curve (*e*), which represents the ratio method, with $\lambda_1 = 0.53$ μm and $\lambda_2 = 1.06$ μm having the equivalent wavelength $\Lambda = 1.06$ μm. The wavelength effect is decidely in favor of the spectral method by a factor of 2. However, the relative emissivity errors may be quite different. Surely one expects $\Delta\epsilon_{\lambda 1}/\epsilon_{\lambda 1}$ to be greater than $\Delta\epsilon_r/\epsilon_r$; perhaps by a factor of 2. Hence, the possibility exists that the two methods are equally attractive, especially if the emissivity estimate for the spectral method will be poor.

There are two other compelling reasons to give further attention to the ratio method: target occlusion and line-of-sight absorption. These are the classic features that make the ratio method attractive. Although it is not clear whether ablation products modify spectral radiance from the target surface, it should be possible in principle to sort out such effects by comparing results using the spectral and ratio methods.

Multispectral Methods

Principles of Multispectral Methods

There are alternative *dual-wavelength* methods, which are extensions of the ratio method, frequently referred to as emissivity *compensation* methods[6] that use an appropriate emissivity function of the form $\epsilon_2 = f(\epsilon_1)$. Of course, the simplest case is that of the ratio method where $\epsilon_1 = \epsilon_2$. Svet's cross-correlation method[7] with a function of the form $\ell n(\epsilon_1 \cdot \epsilon_2) = k$, has been used successfully in precision radiometric measurements on near-black furnaces. Foley[8] has demonstrated a modified-ratio method with a function $\epsilon_1 = \epsilon_2^m$, where $m = (1 - k\lambda_2)/(1 - k\lambda_1)$ suitable for selected metallic and nonmetallic materials with various values of the adjustable constant k. More recently, Anderson[9] developed a *ratio + spectral* method applicable to aluminum alloys for which the temperature equation has the form $T = x_0 T_{\lambda 2} + (1 - x_0)T_r$, where x_0 is the adjustable constant. In order to apply any of these methods, it is necessary to have sufficient emissivity data in order to rationally select the nature of the emissivity function or fix the adjustable constant. With multispectral methods (two or more wavelengths), there is more flexibility in selecting the emissivity function.[10]

Consider now the radiometer that provides the *observed* spectral radiances $L_{\lambda,\mathrm{obs}}(\lambda_i)$ at selected wavelengths λ_i. If the spectral emissivity can be readily expressed in the form $\epsilon = \epsilon(\lambda)$,

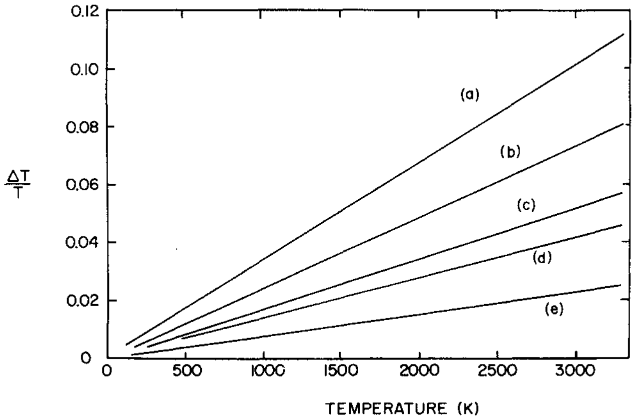

Fig. 2 Relative error of the inferred temperature $\Delta T/T$ for the ratio method with different wavelength (λ_1,λ_2) combinations: a) 0.63, 0.73 μm; b) 0.53, 0.63 μm; c) 0.73, 1.06 μm; d) 0.53, 0.73 μm; and e) 0.53, 1.06 μm for $\Delta\epsilon_r/\epsilon_r = 0.10$.

algorithms can be used to deduce the temperature of the target surface. Two distinct methods referred to as *exact* and *least-squares*, have been treated in the literature.[11,12]

In the exact method, the number of wavelengths for which the spectral radiance is observed corresponds to the number of unknown constants in the emissivity function plus one (the temperature is also unknown). That is, a system of N equations with N unknowns of the form, $L_\lambda(\lambda_i) = \epsilon_i L_{\lambda,b}(\lambda_i, T)$, can be solved exactly. The success of this method strongly depends on whether the emissivity function properly represents the material; furthermore, the presence of noise in the radiance signals can heavily bias the outcome.

The least-squares method avoids the pitfalls of overfitting the data; the observed and modeled radiances are brought into approximate agreement through least-squares fitting routines. The minimum number of wavelengths required to affect an estimate for T (as well as the emissivity function) is equal to the number of known constants in the emissivity function plus two; additional wavelengths provide for minimizing the influence of signal noise.

Constrained Minimization Least-Squares Method

For the least-squares method, the minimization equation can be written as

$$\chi^2 = \sum_{i=1}^{N} (L_{\lambda,\mathrm{mod},i} - L_{\lambda,\mathrm{obs},i}) \qquad (15)$$

corresponding to N wavelength conditions where the *modeled* spectral radiance is of the form

$$L_{\lambda,\mathrm{mod},i} = \epsilon_{\lambda i} c_{1L} \lambda^{-5} \exp(-c_2/\lambda_1 T) \qquad (16)$$

using Wien's law. With a prescribed emissivity function, for example, assumed to be linear and of the form $\epsilon_\lambda = a\lambda + b$, then Eq. (15) is evaluated for all possible values of a, b, and T until a minimum value of χ^2 is obtained. There is no guarantee that realistic values of a and b or T will result from the minimization procedure. If the emissivity function is inappropriate, the results can be disappointing.

A new approach toward improving the outcome of the minimization technique is to place constraints on the emissivity function.[10,13] This obviously requires a priori knowledge of the spectral emissivity, which in many practical situations is easily obtained. Using the linear emissivity function, we can, for example, impose these constraints: $\epsilon_{\min} < \epsilon_\lambda < \epsilon_{\max}$ and $a_{\min} < a < a_{\max}$. Assuming the material behavior is consistent, assigning limits to a (the slope) and limits to ϵ_λ can be readily accomplished. Now the constrained minimization technique based upon Eq. (15) will find the best fit for a, b, and T which satisfies the constraints on a and $\epsilon_{\lambda i}$.

In implementing the method on the carbon-phenolic test data, linear and logarithmic emissivity functions were considered. The most reasonable results were obtained by the emissivity function

$$\epsilon_\lambda = a_0 + a_1 \ln(\lambda) \qquad (17)$$

will be summarized subsequently.

Advantages of Multispectral Methods

One of the principal advantages of the multispectral method is that of signal averaging. Hunter et al.,[14] using 200 spectral bands, demonstrated the utility of the multispectral method for measuring temperatures of a metal junction during a welding process. The large number of spectral bands reduces the influence of signal noise, but unless a realistic emissivity function can be identified, the method may not provide reliable results.

Recently, Nordine[15] reviewed spectral, ratio, and multispectral methods particularly as related to their use in high-temperature materials science studies. According to Nordine, the assumption that emissivities are independent of temperature can lead to significant errors in temperature and thermophysical properties. For such situations, it is not clear which method would be preferred. Nordine suggests that reliable data on liquid surfaces of high-temperature materials are needed in order to develop further understanding in the use of the various types of radiation temperature measurement methods.

Results of the Analyses

Analysis with the Spectral Method

Using the observed spectral radiance temperature data on the carbon phenolic, and following the method outlined in a previous section, surface temperatures and spectral emissivities were calculated. The observed spectral radiance temperatures and spectral emissivities for the carbon-phenolic sample are shown in Figs. 3 and 4, respectively.

The spectral radiance temperatures of Fig. 3 show three interesting characteristics. First, the spectral radiance temperature T_λ is shown to decrease with increasing wavelength as expected. Second, the noise levels for the spectral bands at λ_1 and λ_2 (silicon photodetectors) are significantly lower, perhaps by a factor of five or more, than for the spectral bands at the longer wavelengths λ_3 and λ_4 (PbS and HgCdTe detectors, respectively). This is to be expected as a consequence of the decreased spectral detectivity of the infrared devices. Third, the detailed and general shapes of the curves show some differences and similarities. Note the striking similarity of the two spectral radiance curves obtained with the silicon photodetectors. The time variations appear to be identical; a visual comparison shows excellent registration of peaks and valleys. The curve for

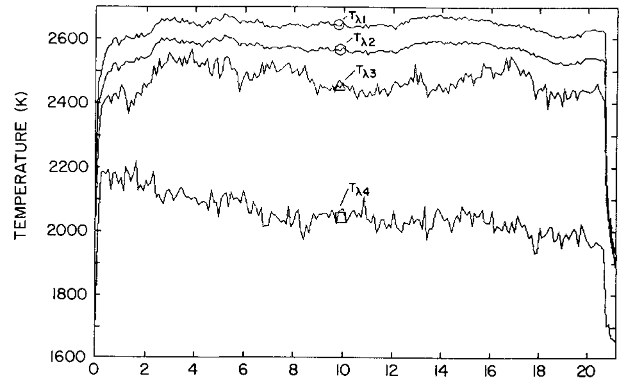

Fig. 3 Spectral radiance temperatures for the carbon-phenolic sample as a function of test time.

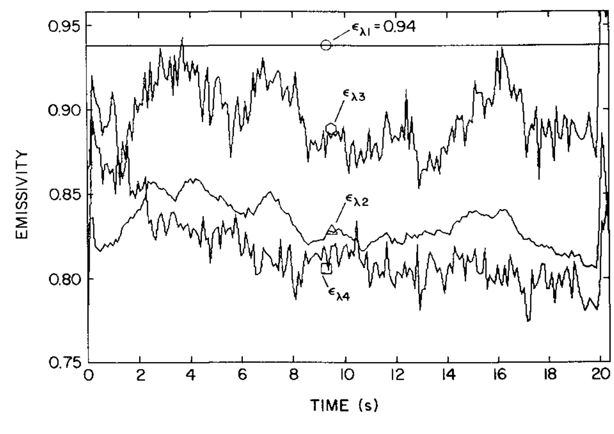

Fig. 4 Spectral emissivity for the carbon-phenolic sample as a function of test time as determined by the spectral method with $\epsilon_{\lambda 1} = 0.94$.

$T_{\lambda 3}$ shows similar trends, but of course the noise level is significantly higher. By contrast, the curve for $T_{\lambda 4}$ displays a different trend. Note that at early times $T_{\lambda 4}$ is shown to rise rapidly, then appears on the average to decrease steadily with increasing time.

These observations on the spectral radiance temperatures for the carbon-phenolic sample raise two important questions. Has any consideration been given to smoothing techniques to reduce noise effects? It is not clear whether it is better to smooth the observed spectral radiance data or the calculated emissivity results? What attention has been paid to the fact that the time constants of the longer wavelength detectors for $T_{\lambda 3}$ and $T_{\lambda 4}$ are most likely much greater than of the silicon detectors (for $T_{\lambda 1}$ and $T_{\lambda 2}$)? This is a very critical feature of the instrumentation design, especially since the target characteristics and/or temperature are changing rapidly with time. Experiences with other multispectral radiometers and radiation thermometers suggest that proper matching of the channels is difficult to achieve and is the most common fault with such instruments.

The spectral emissivities for the carbon-phenolic sample as a function of test time are shown in Fig. 4. The upper curve represents the assumed value at the shortest wavelength $\epsilon_{\lambda 1} = 0.94$. Following the method mentioned previously, the true target temperature is calculated from $T_{\lambda 1}$, following which the spectral emissivities at λ_2, λ_3, and λ_4 are calculated. Note that the spectral emissivity does not decrease steadily with increasing wavelength. Rather, $\epsilon_{\lambda 3}$ is significantly higher than $\epsilon_{\lambda 2}$; such behavior is not expected and no simple explanations based on instrument features and calculation procedures are obvious. Note that generally the $\epsilon_{\lambda 2}$, $\epsilon_{\lambda 3}$, and $\epsilon_{\lambda 4}$ curves show a general decrease with increasing test time. From discussions with the experimental team,[16] the peak-valley behavior, especially evident with $\epsilon_{\lambda 2}$, is related to "layer peeling" of the sample during irradiation. It is not clear whether such a phenomenon should cause a change in temperature, emissivity, or possibly both.

Analysis with the Ratio Method

The observed spectral radiance temperatures of Fig. 3 for the carbon phenolic have been analyzed using the ratio method to obtain the true temperature of the target. The spectral emissivities for the carbon-phenolic sample as a function of test time are given in Figs. 5–8 for assumed values of the emissivity ratio, $\epsilon_r = \epsilon_{\lambda 1}/\epsilon_{\lambda 2} = 1.00$, 1.05, 1.10, and 1.15, respectively.

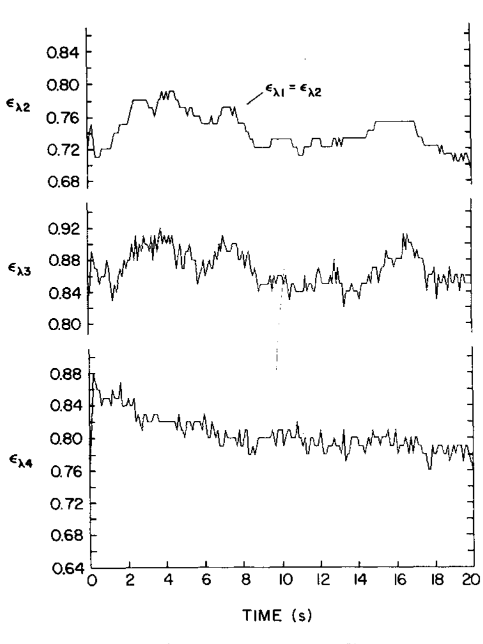

Fig. 5 Spectral emissivity for the carbon-phenolic sample as a function of test time as determined by the ratio method (λ_1,λ_2) with $\epsilon_r = 1.00$.

Table 1 Results of the constrained minimization multispectral method on the carbon-phenolic sample

Point	λ, μm	ϵ_λ	T_λ, K	T, K
1	0.53	0.879	2459	2485
	1.06	0.844	2395	
	3.80	0.780	2266	
	7.90	0.743	1986	
2	0.53	0.907	2612	2632
	1.06	0.872	2543	
	3.80	0.808	2458	
	7.90	0.771	2138	
3	0.53	0.938	2643	2658
	1.06	0.889	2583	
	3.80	0.799	2510	
	7.90	0.748	2077	
4	0.53	0.910	2656	2677
	1.06	0.862	2583	
	3.80	0.772	2467	
	7.90	0.720	2054	
5	0.53	0.923	2642	2659
	1.06	0.874	2569	
	3.80	0.785	2481	
	7.90	0.733	2064	
6	0.53	0.907	2634	2655
	1.06	0.858	2557	
	3.80	0.768	2437	
	7.90	0.716	2038	
7	0.53	0.888	2652	2679
	1.06	0.839	2569	
	3.80	0.750	2452	
	7.90	0.698	2006	
8	0.53	0.892	2673	2700
	1.06	0.843	2593	
	3.80	0.753	2464	
	7.90	0.702	2030	

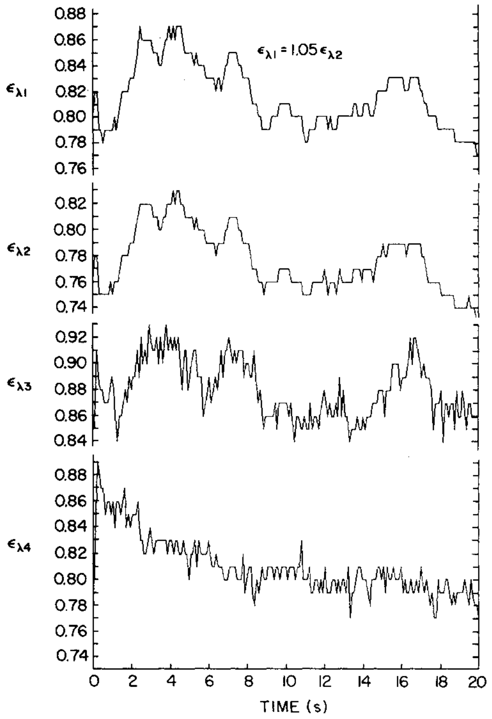

Fig. 6 Spectral emissivity for the carbon-phenolic sample as a function of test time as determined by the ratio method (λ_1,λ_2) with $\epsilon_r = 1.05$.

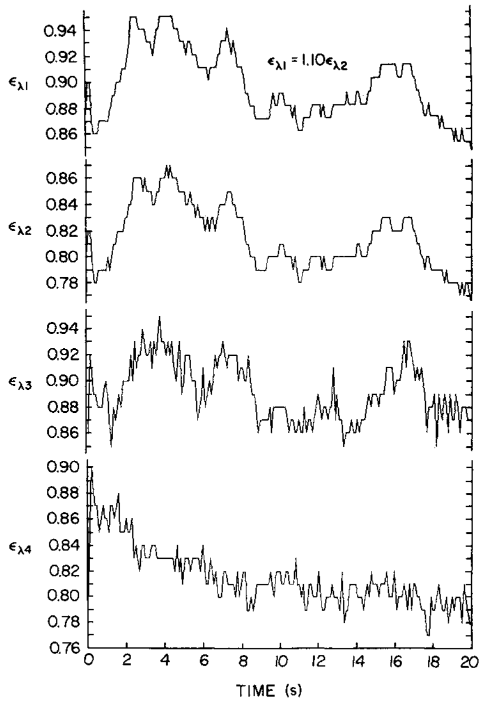

Fig. 7 Spectral emissivity for the carbon-phenolic sample as a function of test time as determined by the ratio method (λ_1,λ_2) with $\epsilon_r = 1.10$.

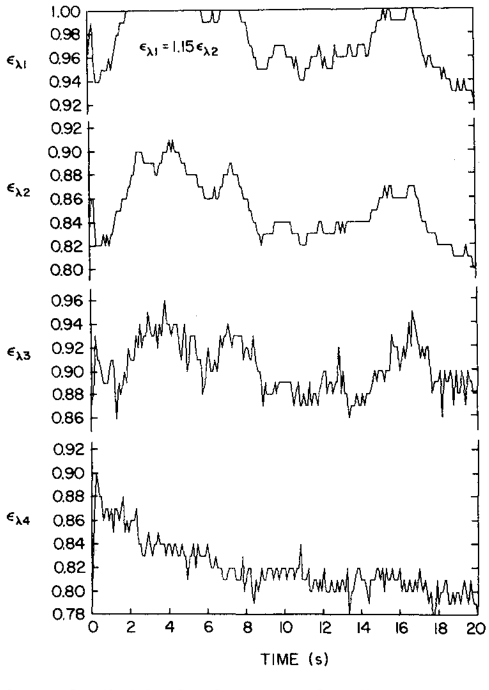

Fig. 8 Spectral emissivity for the carbon-phenolic sample as a function of test time as determined by the ratio method (λ_1,λ_2) with $\epsilon_r = 1.15$.

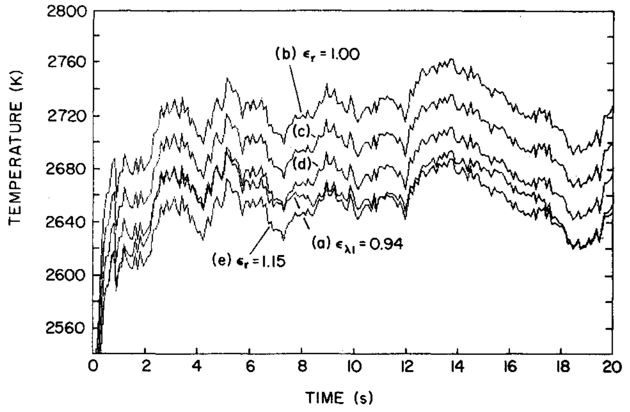

Fig. 9 Surface temperature for the carbon-phenolic sample as a function of test time as determined by the spectral method: a) with $\epsilon_{\lambda 1} = 0.94$ and the ratio method (λ_1,λ_2) with ϵ_r equal to b) 1.00, c) 1.05, d) 1.10, and e) 1.15.

The spectral emissivities calculated from the ratio method, Figs. 5–8, should be compared with those determined for the same sample using the spectral method. From Fig. 4, note that the ratio of $\epsilon_{\lambda 1}/\epsilon_{\lambda 2}$ varies from 1.10–1.15 (for the 2–18-s range, $\epsilon_{\lambda 1} = 0.94$ and $\epsilon_{\lambda 2} = 0.85$–$0.82$). Hence, we should expect the results of Figs. 7 and 8 for the ratio method with $\epsilon_r = 1.10$ and 1.15 to be the most appropriate for comparison of the results of Fig. 4 for the spectral method.

Consider the results of Fig. 7 (ratio method, $\epsilon_r = 1.10$) with those of Fig. 4 (spectral method, $\epsilon_{\lambda 1} = 0.94$). The points of comparison are as follows: 1) the ratio results for $\epsilon_{\lambda 1}$, $\epsilon_{\lambda 2}$, and $\epsilon_{\lambda 3}$ show the same temporal variation as the spectral results; 2) the magnitudes of the ratio and spectral results are nearly the same; note that the ratio method also predicts $\epsilon_{\lambda 3} > \epsilon_{\lambda 2}$; and 3) the variability of the ratio method emissivity spectra for $\epsilon_{\lambda 1}$ and $\epsilon_{\lambda 2}$ is much larger than for the corresponding spectral method emissivity spectra while the variability for the $\epsilon_{\lambda 3}$ and $\epsilon_{\lambda 4}$ for both methods is about the same. Perhaps most encouraging is the favorable intercomparison between the $\epsilon_{\lambda 4}$ results by both methods.

Considering the results of Fig. 8 (ratio method, $\epsilon_r = 1.15$) with those of Fig. 4, similar conclusions can be reached, as for the case when $\epsilon_r = 1.10$. With $\epsilon_r = 1.15$, the magnitude of $\epsilon_{\lambda 1}$ is higher than with $\epsilon_r = 1.10$, maybe slightly too high (0.96) for what was expected for this material.

A further comparison between the spectral and ratio method results is presented in Fig. 9 for the carbon-phenolic sample temperature. Curve (a) represents the results using the spectral method with the assumed value $\epsilon_{\lambda 1} = 0.94$. Curves (b–e) represent the results using the ratio method with various assumed values for $\epsilon_r = \epsilon_1/\epsilon_2$. Note that the curves for $\epsilon_r = 1.00$ and 1.05 are markedly higher than the curve representing the spectral method, whereas the $\epsilon_r = 1.10$ and 1.15 curves bracket the curve for the spectral method. The overall difference between the two ratio curves amounts to 20 K. Further confidence in the estimate for the true temperature stems from the similarity of the temporal variations for both methods.

For the present sample material, the ratio method does not offer any advantage over the spectral method, primarily because of the ability to make a reliable estimate for $\epsilon_{\lambda 1}$. This may not be the situation for other materials especially with lower emissivity values and then it may be desirable to process the observations using the ratio method. In these circumstances, it also would be desirable to have the bandpasses, λ_1 and λ_2, more closely spaced so that ϵ_r will approach unity.

Analysis with Multispectral Methods

Because of the extensive computational requirements for performing the many minimization trials to be undertaken, it was more appropriate to select test points rather than to consider the entire set. Table 1 provides a summary of the constrained minimization method using the emissivity function of Eq. (17). The constraints of the spectral emissivities at λ_1 and λ_4 were 0.94 and 0.91, respectively, with an allowable span of ± 0.06 emissivity units. Furthermore, the slope of the function was constrained to the range -0.0704 to 0.0296. It should be recognized that a priori knowledge of the emissivity spectra is required to set the constraints and that, in general, more precise results will be obtained with tighter constraints.

The observed spectral radiance temperature T_λ for the four wavelengths λ_i are shown in columns four and two, respectively, of Table 1. The predicted emissivity ϵ_λ and true temperature T_{act} are listed in columns three and five, respectively. For all points examined, the solution fell outside the constraints; that is, one or more of the emissivity function magnitude or slope constraints was not satisfied.

Although the emissivity and predicted true temperature results are reasonable, the entire analysis is faulty because the emissivity spectra for the carbon-phenolic sample is not logarithmic (or linear) but, recalling that $\epsilon_{\lambda 3} > \epsilon_{\lambda 2}$, it is evident that the emissivity function must exhibit appreciable curvature. Such being the case, the minimization method loses any advantage if a complicated emissivity function needs to be employed. Furthermore, a poor outcome using the method is expected because of the wide separation of the wavelengths. Experiences have shown the wavelengths should be more closely spaced in the spectral range on the short side of the blackbody maximum. For the present application with temperatures above 2500 K, the most appropriate wavelengths would be in the range 0.5–1.0 μm. Quite likely in this range the emissivity spectra is more regular and a simple linear (logarithmic) function would be satisfactory.

Summary and Conclusions

The spectral method for determining the true temperature T and spectral emissivities ($\epsilon_{\lambda 2}$, $\epsilon_{\lambda 3}$, $\epsilon_{\lambda 4}$) from the observed spectral radiance temperatures ($T_{\lambda 1}$, $T_{\lambda 2}$, $T_{\lambda 3}$, $T_{\lambda 4}$) of the carbon-phenolic sample has considerable merit. The method has a sound theoretical basis since, for this material, the spectral emissivity at the shortest wavelength $\epsilon_{\lambda 1}$ can be estimated with good precision (0.94). If the uncertainty of this value is $\pm 10\%$, the uncertainty of the true temperature at 2650 K (see Fig. 9) resulting from emissivity effects is only ± 26 K ($\pm 1.0\%$) and the uncertainties in the spectral emissivities at 1.06, 3.78, and 7.8 μm are 5.0, 1.8, and 1.4%, respectively. It should be recognized that a 10% uncertainty for $\epsilon_{\lambda 1}$ (0.53 μm) brackets the range 0.83–1.0, so there is high confidence that the assumed value is realistic and therefore the resulting temperature and spectral emissivity are likewise determined with confidence.

For situations where the spectral emissivity $\epsilon_{\lambda 1}$ cannot be estimated with confidence, for example, as would be the case for low-emissivity materials, the ratio method may offer an advantage. Because of the higher effective wavelength with the ratio method (Λ vs λ_1), the error equation shows that the effects of assumed emissivity uncertainty is nearly doubled. However, since $\Delta\epsilon_r/\epsilon_r$ rather than $\Delta\epsilon_{\lambda 1}/\epsilon_{\lambda 1}$ is important, the effective wavelength effect may be mitigated. For the carbon-phenolic sample, a value of $\epsilon_r = 1.10$–1.15 with the ratio method was found to be in best agreement with the spectral method results. Clearly, to use the ratio method, it is necessary to have some knowledge of the sample emissivity spectra in order to rationally estimate ϵ_r.

An advantage of the ratio method is the potential for minimizing line-of-sight effects owing to absorption by ablation products. Without more detailed optical measurements, it is not possible to determine whether such effects are present in the data of this study.

Shortcomings of this evaluative study on the method are the lack of spectral emissivity data for the sample at elevated temperatures, especially at the melting point, and the absence of observations on a reference target material for which detailed thermophysical properties are well-known. Data on well-characterized materials of interest to the present application using conventional laboratory experimental methods are essential if full confidence in the results of laser irradiation studies is to be established.

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