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Temperature Measurement of a Glass Material Using a Multiwavelength Pyrometer

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TEMPERATURE MEASUREMENT OF A GLASS MATERIAL USING A MULTIWAVELENGTH PYROMETER

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Introduction

Temperature measurement of a substance that is transparent using the traditional 1-color, 2-color and other pyrometers has been difficult. The radiation detected by pyrometers do not come from a well defined location in the transparent body. The multiwavelength pyrometer developed at the NASA Lewis Research Center can measure the surface temperature of many materials. We show in this paper that it also measures the surface and a bulk sub-surface temperature of transparent materials like glass.

Method

The multiwavelength pyrometer consists of a spectrometer and a computer. The computer controls the spectrometer to acquire a spectrum and performs the subsequent data analysis to determine the temperature. The temperature of the measured surface dictates the spectral region in which the spectrometer will operate. The spectral region can be from 0.5 to 2.5 μm, 1.3 to 4.5 μm or 2 to 14.5 μm depending on the particular requirements. The emitted/transmitted radiation is described by Planck's law of black body radiation[1]

$$L_\lambda = \varepsilon_\lambda \tau_\lambda \frac{c_1}{\lambda^5} \frac{1}{\exp(c_2 / \lambda T) - 1} = \varepsilon_\lambda \tau_\lambda \frac{c_1}{\lambda^5} \exp(-c_2 / \lambda T) \frac{1}{1 - \exp(-c_2 / \lambda T)} \tag{1}$$

where c_1, c_2 are the radiation constants, L_λ is the radiation intensity, ε_λ is the emissivity, and τ_λ is the transmissivity of the optical medium between the pyrometer and the radiation source at wavelength λ.

The intensity of radiation at wavelength λ, emitting from a slab of thickness dx, inside the transparent material at a distance x from the surface, detected by the pyrometer outside the transparent material, is given by[1]

$$dL_\lambda = (1 - R) a \exp(-ax) \frac{c_1}{\lambda^5} \frac{1}{\exp(c_2 / \lambda T(x)) - 1} dx \tag{2}$$

a is the absorption coefficient of the transparent material, T(x) is the temperature at x, R is the fraction of radiation that is reflected back to the medium, therefore 1-R is the fraction that escapes being reflected. The total contribution from all the slabs from x=o to x=D, where D is the total thickness of the transparent medium is obtained by integrating Eqn. 2 from 0 to D

$$L_\lambda = (1 - R) \frac{c_1}{\lambda^5} \int_0^D a \exp(-ax) \frac{1}{\exp(c_2 / \lambda T(x) - 1} dx \tag{3}$$

In the long wavelength region, the glass is opaque, the radiation emitted is from the surface according to Eqn. 1, which for data analysis, is rewritten as

$$\left(\frac{\mathrm{Ln}\left(\frac{c_1}{\lambda^5} \frac{1}{L_\lambda} \right)}{c_2 / \lambda} \right) - \frac{\mathrm{Ln}\left(1 - \exp(-\frac{c_2}{\lambda T}) \right)}{c_2 / \lambda} = \frac{1}{T} - \frac{\lambda}{c_2} \mathrm{Ln}\left(\varepsilon_\lambda \tau_\lambda \right) \tag{4}$$

This is the working equation of the traditional 1-color pyrometry method which requires knowing the emissivity and or transmissivity. For the multiwavelength pyrometer, neither quantity is required to determine the temperature. Because the quantity $(1-\exp(-c_2/\lambda T))$ is practically unity at short wavelengths, its logarithm would be near zero. We observe from Eqn. 4 that plotting the quantity $y=\mathrm{Ln}(c_1/(\lambda^5 L_\lambda))/(c_2/\lambda)-\mathrm{Ln}(1-\exp(-c_2/\lambda T))/(c_2/\lambda^5)$ as a function of λ would result in a straight line if $\mathrm{Ln}(\varepsilon_\lambda \tau_\lambda)$ is wavelength independent, with its slope given by $\mathrm{Ln}(\varepsilon_\lambda \tau_\lambda)/c_2$. The quantity $1/y$ at each wavelength λ is often referred to as the radiant temperature. The intercept of the straight line at λ=0 is $1/T$, the reciprocal of the desired unknown temperature.

In the short wavelength region, the radiation originates from inside the transparent material. In general there will be a temperature profile T(x) which is a function of x. We assumed that a characteristic temperature T_i can be defined, and Eqn. 3 can be rewritten as

$$L_\lambda = (1-R)\frac{c_1}{\lambda^5}\exp(-c_2/\lambda T_i)\int_0^D a\exp(-ax)\frac{\exp(c_2/\lambda T_i)}{\exp(c_2/\lambda T(x))-1}dx \tag{5}$$

If $\exp(c_2/\lambda T) >> 1$, Eqn. 5 can be simplified to

$$L_\lambda = \frac{c_1}{\lambda^5}\exp(-c_2/\lambda T_i)I(T_i,\lambda) \tag{6}$$

where

$$I(T_i,\lambda) = \int_0^D (1-R)a\exp\left(-ax + \frac{c_2}{\lambda}\left(\frac{1}{T_i} - \frac{1}{T(x)}\right)\right)dx \tag{7}$$

Transforming Eqn. 6 into inverse radiant temperature similar to Eqn. 4, we have

$$\left(\frac{\mathrm{Ln}\left(\frac{c_1}{\lambda^5}\frac{1}{L_\lambda}\right)}{c_2/\lambda}\right) = \frac{1}{T_i} - \frac{\lambda}{c_2}\mathrm{Ln}\left(I(T_i,\lambda)\right) \tag{8}$$

If $I(T_i,\lambda)$ is independent of λ, a plot of the quantity on the left vs λ will give a straight line, with the intercept equal to the reciprocal of the temperature T_i. The extent to which this assumption is true will be determined by how well the data of the experiment agrees with this interpretation.

Results

Six spectra of a glass sample raised in temperature by a propane torch are recorded by the multiwavelength pyrometer. The sample measured approximately 6 mm square. These spectra are shown in Fig. 1, from which it can be seen that the temperature has varied little during the time (16 seconds) that each spectrum was recorded. Most of the radiant energy in the spectra is contained in the spectral region longer than 1 μm. One of them is fitted to a Planck curve of temperature 1194 K and emissivity 0.74 at all wavelengths (Fig. 2). The agreement between the data and the calculated curve is extremely good. The deviation near 2.4 μm is due to poor signal to noise. We concluded that a predominant portion of the radiation is surface emission at wavelengths longer than 1 μm. The temperature of the surface is thus determined to be 1194 K. We also analyzed the data according to the inverse radiant temperature transformation method. The result is shown in Fig. 3. It is obvious that the spectrum consists of two regions. In the long wavelength region, the radiation is from the opaque surface, and the analysis according to Eqn. 4 resulted in a straight line, the intercept of which also yielded a temperature of 1194 K. In the short wavelength region, the data showed that plotting the data according to Eqn. 8 produced a different straight line, implying that the integral defined by Eqn. 7 is indeed independent of wavelength. The intercept of this straight line yielded a bulk temperature of 1136 K. This is about 60 K lower that the surface. It shows that the short wavelength radiation in the spectrum is from the bulk.

Conclusion

Temperature measurement of a glass sample heated by an open propane torch flame was made using a multiwavelength pyrometer. The glass is opaque at the longer wavelength and transparent at the short wavelength. The multiwavelength pyrometer determined a surface glass temperature from the long wavelength data, and a sub-surface bulk glass temperature, from the short wavelength data.

Acknowledgment

The sample measured in this experiment was kindly provided by Dr Vijay Murgai of the Libbey-Owens-Ford Company.

Reference

1. DeWitt, D.P., Nutter, G.D., Theory and Practice of Radiation Thermometry, John Wiley & Sons, New York, 1988.

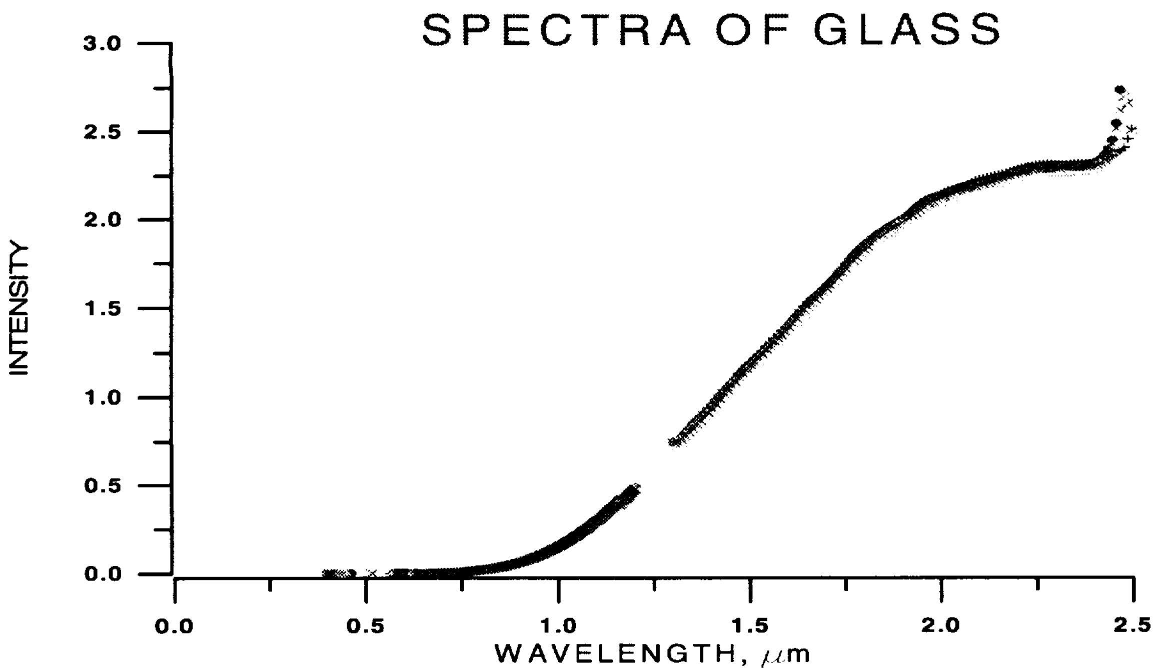

Figure 1—Spectra of Glass

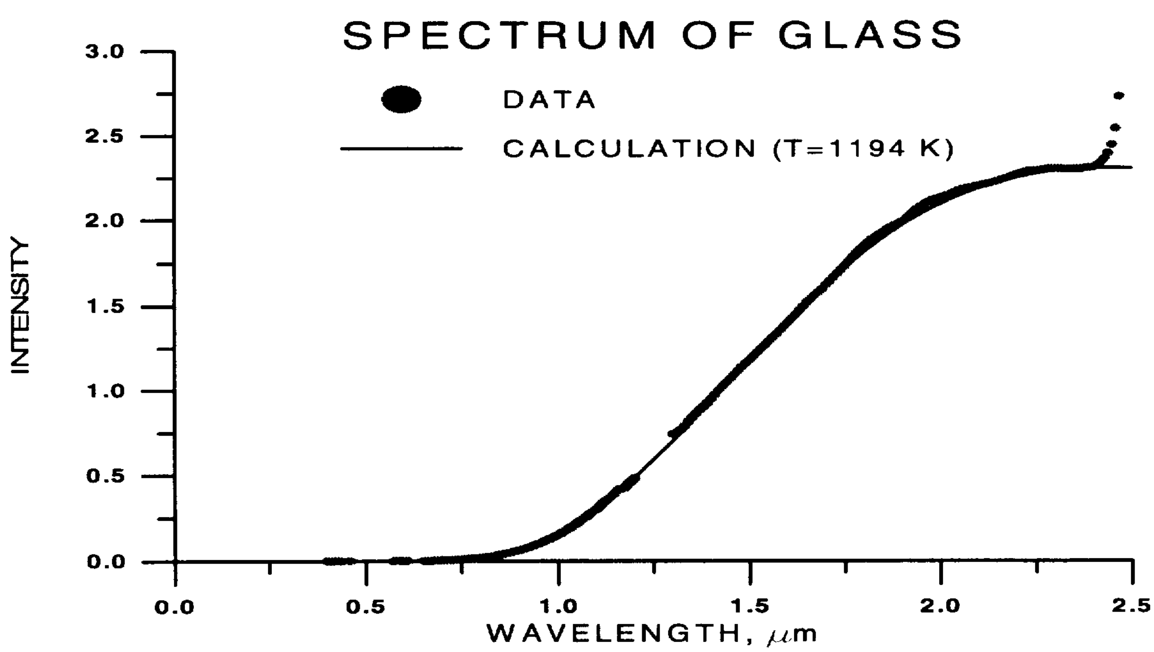

Figure 2—Fitted glass spectrum

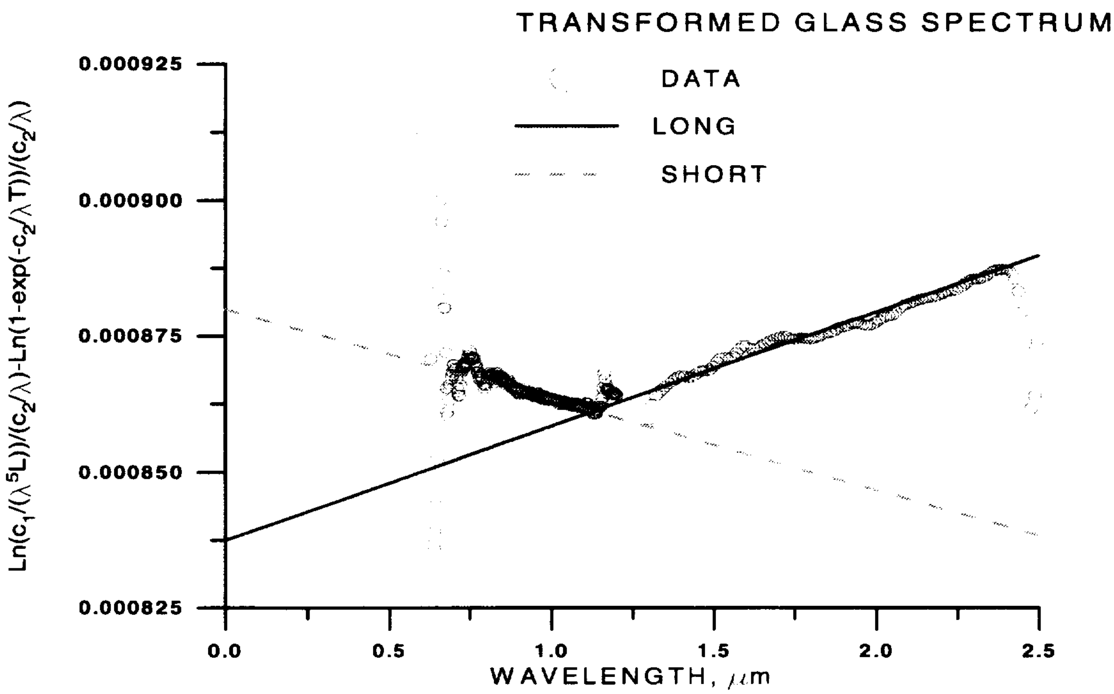

Figure 3—Fitted transformed spectrum

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