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Self Calibration of a 2-wavelength Pyrometer

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November 1998

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Introduction

Pyrometers require calibrations to determine their instrument constants before they can be used in remote temperature measurements (Ref. 1) These constants reflect the combined effects of detector response, the transmissivities of intervening optical media (windows and gases) and the emissivity of the measured surface. We describe here the principle and the demonstration of a self calibrating 2-wavelength pyrometer.

Method

The basic hardware of the pyrometer is a spectrometer equipped with detector or detectors sensitive at two wavelengths. In response to radiation from a radiating surface, the detector response at different wavelengths are simultaneously recorded during a time in which the measured surface experienced a temperature excursion over an unknown range.

$V(\lambda, t)$ is the response of the pyrometer detector at wavelength λ at time t when the temperature of the emitting surface is $T(t)$. The response of the detector to radiation emitted from the measured surface is a voltage given by

$$V(\lambda, t) = g_{\lambda} \epsilon_{\lambda} \tau_{\lambda} L(\lambda, T(t)) \quad (1)$$

where g_{λ} is the detector's spectral electrical response constant to radiation at wavelength λ , ϵ_{λ} is the emissivity of the emitting surface and τ_{λ} is transmissivity of the intervening medium or window. The intensity of the radiation arriving at the detector is $\epsilon_{\lambda} \tau_{\lambda} L(\lambda, T(t))$ where

$$L(\lambda, T(t)) = \frac{c_1}{\lambda^5} \frac{1}{(\exp(c_2 / \lambda T(t)) - 1)} \quad (2)$$

is the spectral radiation intensity of a black body at temperature $T(t)$ obeying Planck's equation. c_1 and c_2 are the radiation constants.

Assuming no time dependence in g_{λ} , ϵ_{λ} and τ_{λ} , a new quantity $A(\lambda)$ is defined:

$$A(\lambda) = g_{\lambda} \epsilon_{\lambda} \tau_{\lambda} \quad (3)$$

The assumption of no time dependence in g_{λ} , ϵ_{λ} and τ_{λ} is in general valid for most materials. It is most true for g_{λ} because detectors have good short and long term stability. ϵ_{λ} of a surface may vary by a large amount due to oxidation or thermal changes during the temperature excursion. Variation of τ_{λ} could be due to absorption by gases whose concentration in the optical path may vary. At the two wavelengths λ_1 and λ_2 , data are recorded from time $t = 0$ to $t = t_{\text{final}}$. Consider the following quantities:

$$V(\lambda_1, 0) = A(\lambda_1)L(\lambda_1, T(0)) \quad (4)$$

$$V(\lambda_1, t) = A(\lambda_1)L(\lambda_1, T(t)) \quad (5)$$

$$V(\lambda_2, 0) = A(\lambda_2)L(\lambda_2, T(0)) \quad (6)$$

$$V(\lambda_2, t) = A(\lambda_2)L(\lambda_2, T(t)) \quad (7)$$

Eqn (6) can be transformed into

$$\exp\left(\frac{1}{T(0)}\right) = \left[\frac{A(\lambda_2)}{V(\lambda_2, 0)} \frac{c_1}{\lambda_2^5} + 1 \right]^{\frac{\lambda_2}{c_2}} \quad (8)$$

Similarly Eqn (7) is transformed into

$$\exp\left(\frac{1}{T(t)}\right) = \left[\frac{A(\lambda_2)}{V(\lambda_2, t)} \frac{c_1}{\lambda_2^5} + 1 \right]^{\frac{\lambda_2}{c_2}} \quad (9)$$

The ratio of Eqn (4) and Eqn (5) is

$$y(t) = \frac{V(\lambda_1, 0)}{V(\lambda_1, t)} = \frac{\exp(c_2 / \lambda_1 T(0)) - 1}{\exp(c_2 / \lambda_1 T(t)) - 1} \quad (10)$$

Eqns (8) and (9) are used to eliminate T(0) and T(t) from Eqn (10) and define

$$x(\lambda_2, t) = \frac{1}{V(\lambda_2, t)} \quad (11)$$

from which we obtain

$$y(t) = \frac{V(\lambda_1, 0)}{V(\lambda_1, t)} = \frac{\left[\frac{A(\lambda_2)}{V(\lambda_2, 0)} \frac{c_1}{\lambda_2^5} + 1 \right]^{\frac{\lambda_2}{\lambda_1}} - 1}{\left[\frac{A(\lambda_2)}{V(\lambda_2, t)} \frac{c_1}{\lambda_2^5} + 1 \right]^{\frac{\lambda_2}{\lambda_1}} - 1} = \frac{\left[A(\lambda_2) \frac{c_1}{\lambda_2^5} x(\lambda_2, 0) + 1 \right]^{\frac{\lambda_2}{\lambda_1}} - 1}{\left[A(\lambda_2) \frac{c_1}{\lambda_2^5} x(\lambda_2, t) + 1 \right]^{\frac{\lambda_2}{\lambda_1}} - 1} \quad (12)$$

Analyzing y(t) as defined by Eqn (10) as a function of x(λ₂,t) which is defined by Eqn (11) will determine the constant A(λ₂). With A(λ₂) determined, the temperature in Eqn (2) at any time t is determined to be

$$T(t) = \frac{c_2 / \lambda_2}{Ln\left(\frac{A(\lambda_2)}{V(\lambda_2, t)} + 1\right)} \quad (13)$$

Experiment

To illustrate the working of this pyrometry method, a commercial spectrometer/radiometer was used. It possessed an indium antimonide/mercury cadmium telluride detector and a filter wheel monochromator for radiation from 1.3 to 14.5 μm . Normal radiometer calibration was omitted. The spectrometer was exposed to radiation from a black body furnace whose temperature was gradually increased from room temperature to 1300 K. The temperature of the furnace was constant during the time the spectrometer acquired a spectrum. At each temperature, the detector output voltage spectrum was recorded (Fig 1). In Figure 1, the different traces in the spectrum correspond to different temperatures. The temperature of the black body furnace was measured using a chromel-alumel thermocouple.

Results

Voltage data at different times (hence at different temperatures) for radiation at wavelengths $\lambda = 2$ and $\lambda = 5 \mu\text{m}$ were transformed according to Eqns (10) and (11). Two analyses were performed on the data. In the first analysis, one wavelength was treated as λ_1 while the other wavelength was treated as λ_2 . In the second analysis, the designation of λ_1 and λ_2 was reversed. The results are shown in Fig. 2 and Fig. 3. Calculations performed according to Eqn (12) for the value of $A(\lambda)$ are shown in both figures. The value of $A(\lambda)$ was determined using the least squares method. With the determined values of $A(\lambda)$ used in Eqn (13), the temperatures at different times are calculated. Comparison of these temperatures with the thermocouple produced temperatures are shown in Fig. 4. The agreements are excellent. The straight line through the data is a plot of slope equal 1.

Conclusion

The working of a self calibrating 2-wavelength pyrometer is demonstrated. The pyrometer calibration constant is automatically determined by the pyrometer. The voltage response of detectors at two different wavelengths at many different unknown temperatures was analyzed to determine the calibration constants and used to measure temperatures at subsequent times.

References

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

VOLTAGE SPECTRUM

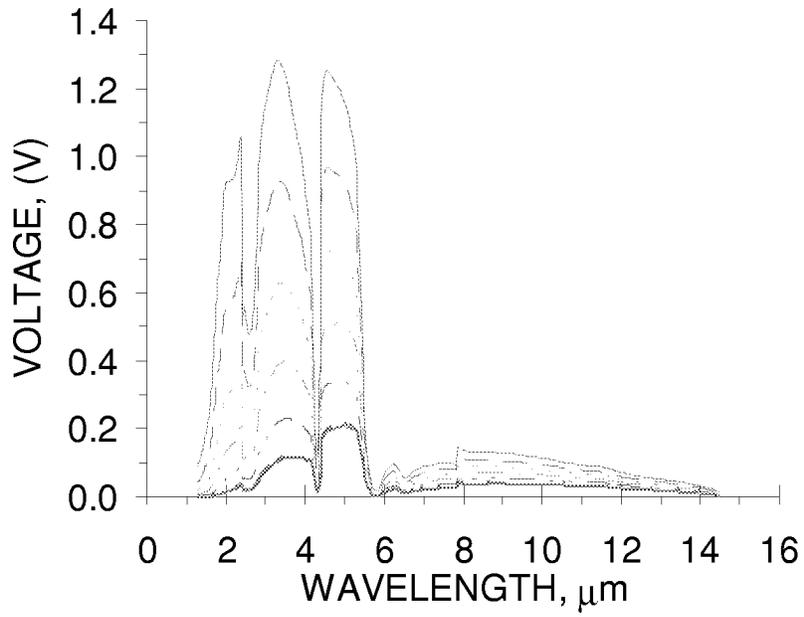


Figure 1

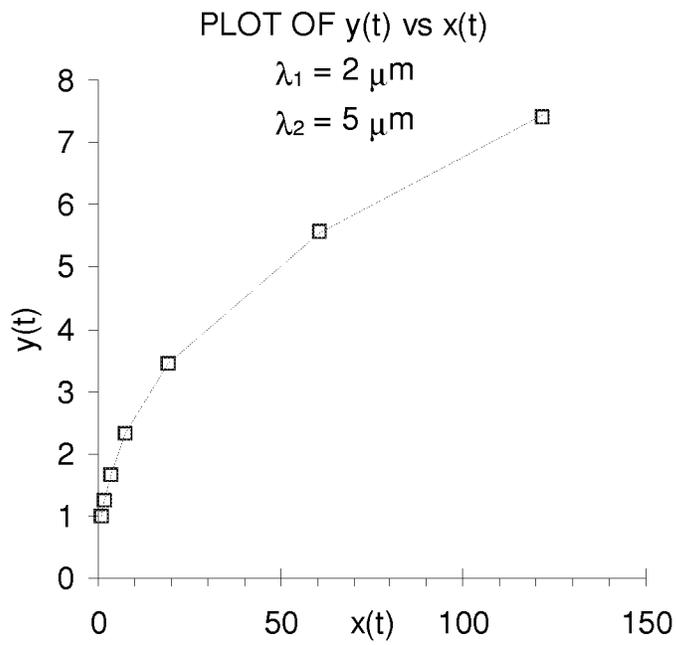


Figure 2

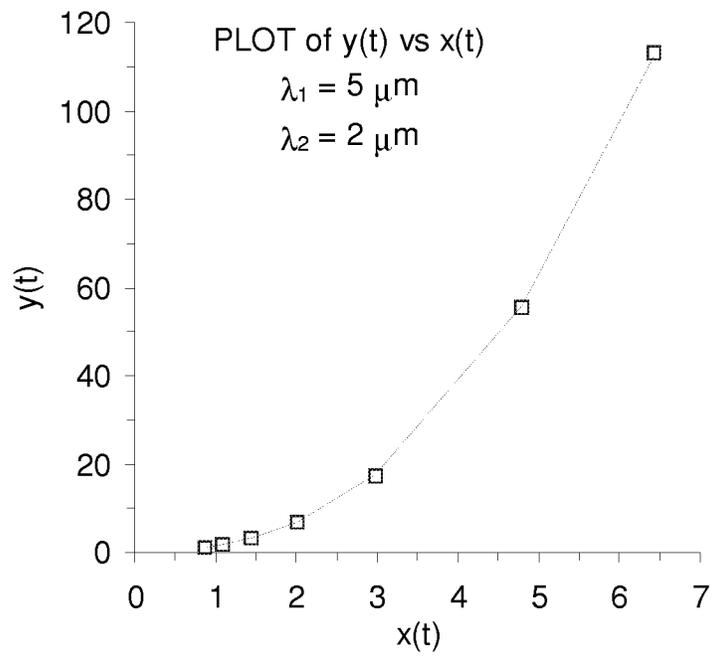


Figure 3

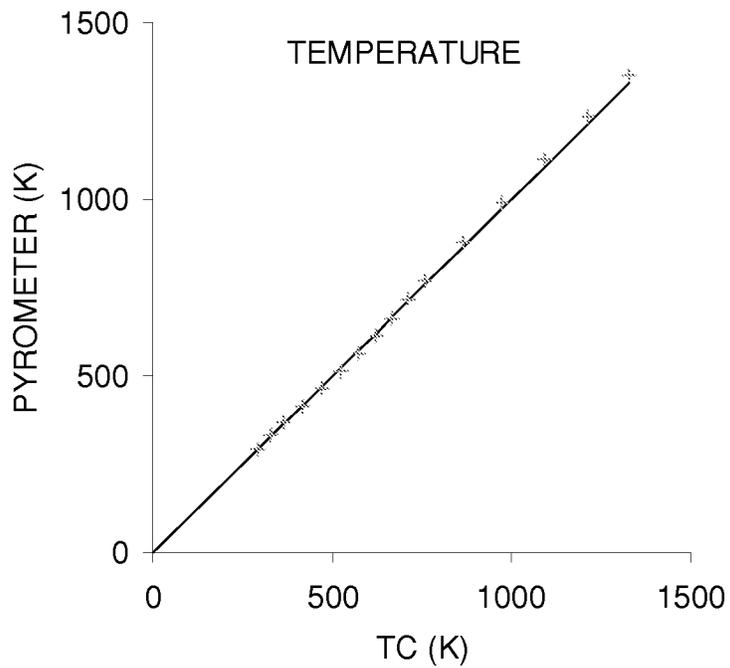


Figure 4

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