International Journal of Thermophysics, Vol. 26, No. 4, July 2005 (© 2005)
DOI: 10.1007/s10765-005-6724-6

Processing Method of Multi-Wavelength Pyrometer Data for Continuous Temperature Measurements[1]

X. G. Sun,[2,3] G. B. Yuan,[2] J. M. Dai,[2] and Z. X. Chu[2]

The processing of multi-wavelength pyrometer data is a problem that needs further improvements. The solutions developed in earlier decades generally assumed one particular mathematical relation for emissivity versus wavelength in the wavelength range of the measurements. Sometimes this assumption worked and produced acceptable results, but in many other cases this approach provided erroneous results. Individual results were strongly dependent on the assumed mathematical relation that often needed some prior knowledge of the emissivity behavior in the wavelength range. A new data processing method for a multi-wavelength pyrometer for continuous temperature measurements is presented. A linear relation between emissivity and true temperature at different wavelengths is assumed. Based on this assumption, the true temperatures and spectral emissivities at the two continuous temperature measurement points can be simultaneously calculated. Some experimental results for the practical data processing of measurements performed on a solid propellant rocket engine show that the difference between the calculated true temperature and the theoretical true temperature indicated by the rocket engine designer is within ± 20 K.

KEY WORDS: data processing; emissivity; multi-wavelength pyrometer; temperature measurement.

1. INTRODUCTION

The technique of multi-wavelength pyrometry, which is mainly used for dynamic measurements of the true temperature and thermophysical properties of high temperature and ultrahigh temperature targets, has been

[1] Paper presented at the Seventh International Workshop on Subsecond Thermophysics, October 6–8, 2004, Orléans, France.

[2] Department of Automation Measurement and Control Engineering, Harbin Institute of Technology, Harbin 150001, P.R. China.
[3] To whom correspondence should be addressed. E-mail: sxg@hit.edu.cn

developed in Europe and America since the 1980s [1, 2]. If a multi-wavelength pyrometer has n channels, there are only n equations but $(n+1)$ unknown parameters, that is, the true temperature T and n spectral emissivities $\varepsilon(\lambda_i, T)$. So a function between emissivity and wavelength must be assumed [3,4]. A frequently used assumption between emissivity and wavelength λ is

$$\ln \varepsilon(\lambda, T) = a + b\lambda \quad (1)$$

Based on Eq. (1), the true temperature and spectral emissivities can be calculated by the least-squares method [5]. A problem occurs when the function between the emissivity and wavelength of the real target is not in accordance with Eq. (1); the calculated results of the true temperature and spectral emissivities are very different from that of the real target. So the data processing method of multi-wavelength pyrometry based on Eq. (1) does not work for all materials [6].

In order to solve the true temperature and spectral emissivity measurements of most engineering materials, a new data processing method of multi-wavelength pyrometry is presented here, which requires no limitation between emissivity and wavelength, but requires a linear relation between emissivity and true temperature at different wavelengths as shown in the following equation:

$$\varepsilon_i = \varepsilon_{i0}[1 + k(T - T_0)] \quad (2)$$

where ε_{i0} is the spectral emissivity at wavelength λ_i and true temperature T_0 and ε_i is the spectral emissivity at wavelength λ_i and true temperature T.

2. BASIC PRINCIPLE

The basic principle of the algorithm is as follows:

(1) Estimate the emissivity value of channel i at the first temperature point from the output of channel i at the first temperature point and the estimated value of the first temperature.

(2) Change the estimated emissivity value of channel i at the first temperature point within a certain small range.

(3) Get the emissivity of channel i at the second temperature point based on Eq. (2).

(4) Corresponding to the emissivity of channel i at the second temperature point in a different group, the true temperature of channel i at the second temperature point in a different group can

be calculated. When the variance of the calculated true temperatures of every wavelength at the second temperature point in a certain group is minimized, it is the true temperature of the second temperature point. The reason is that only when the hypothesis (Eq. (2)) is similar to the true condition of the measured target, the calculated true temperatures of every wavelength at the second temperature point approach the same value.

(5) Then the emissivity of channel i at the second temperature point, the emissivity of channel i at the first temperature point, and the true temperature at the first temperature point can be calculated.

The algorithm is introduced as follows in detail.

Consider a multi-wavelength pyrometer consisting of n channels at known wavelengths; the signal measured at channel i of such a pyrometer is given by

$$V_i = A_i \varepsilon_i \lambda_i^{-5} \exp\left(-\frac{c_2}{\lambda_i T}\right) \quad (i = 1, 2, \ldots, n) \tag{3}$$

where A_i is a calibration factor which depends on the wavelength. The detector sensitivity, geometry, absorption through windows, and the first radiation constant are all taken into account in the constant A_i.

The signal measured at channel i against a reference blackbody furnace at a known temperature T_R is given by

$$V_{iR} = A_i \lambda_i^{-5} \exp\left(-\frac{c_2}{\lambda_i T_R}\right) \quad [\text{here } \varepsilon_i = 1.0] \tag{4}$$

Rearranging Eqs. (3) and (4) gives

$$\frac{V_i}{V_{iR}} = \varepsilon_i \exp\left(-\frac{c_2}{\lambda_i T}\right) \exp\left(\frac{c_2}{\lambda_i T_R}\right) \tag{5}$$

The output of channel i at the first temperature point is designated as V_{i1} and the estimated value of the first temperature as T_0, then the estimated emissivity value of channel i at the first temperature point can be written as

$$\varepsilon_{i0} = \frac{V_{i1}}{V_{iR}} \exp\left(\frac{c_2}{\lambda_i T_0}\right) \exp\left(-\frac{c_2}{\lambda_i T_R}\right) \tag{6}$$

Assum $\varepsilon > 0, \eta > 0, M > 0, \varepsilon_{i1} \in (\varepsilon_{i0} - \varepsilon, \varepsilon_{i0} + \varepsilon), k \in (-\eta, \eta), T \in (T_0 - M, T_0 + M)$, then the emissivity at temperature T is

$$\varepsilon_i = \varepsilon_{i1}[1 + k(T - T_0)] \tag{7}$$

Corresponding to a different channel i we can get a different T, so we note T_{i2} as the calculated temperature of channel i at the second temperature point. Rearranging Eq. (5) gives

$$T_{i2} = \frac{1}{\frac{1}{T_R} + \frac{\lambda_i}{c_2} \ln\left(\frac{\varepsilon_i \cdot V_{iR}}{V_{i2}}\right)} \tag{8}$$

where V_{i2} is the output of channel i at the second temperature point.

Combining Eqs. (7) and (8) leads to

$$T_{i2} = \frac{1}{\frac{1}{T_R} + \frac{\lambda_i}{c_2} \ln\left(\frac{\varepsilon_{i1}[1+k(T_{i2}-T_0)]\cdot V_{iR}}{V_{i2}}\right)} \tag{9}$$

Based on Eq. (9), T_{i2} can be calculated by an iterative method. The criterion of the calculation method is the minimum variance of T_{il}, which is

$$F_{\min} = \sum_{l=1}^{2} \sum_{i=1}^{n} [T_{il} - E(T_l)]^2 \tag{10}$$

where $E(T_l) = \frac{1}{n} \sum_{i=1}^{n} T_{il}$

3. EXPERIMENTAL RESULTS

In order to verify the above-mentioned algorithm, we use practical data performed on a solid propellant rocket engine. The eight-wavelength pyrometer developed here was used in ground experiments. The effective wavelengths and outputs at the reference temperature T_R (T_R = 2252 K) are shown in Table I.

The measured point in the ground experiment is 3–5 cm away from the engine nozzle exit plane. The reason to choose the measured point near the nozzle exit is to compare the calculated true temperature with the theoretical true temperature indicated by the rocket engine designer.

The pyrometer acquires outputs of eight channels in 5 ms. The whole experiment lasts 20 s. In order to record the whole experiment process

Table I. Effective Wavelengths of the Pyrometer and Outputs at the Reference Temperature (T_R = 2252 K)

Channel i	1	2	3	4	5	6	7	8
λ_I (μm)	0.574	0.592	0.623	0.654	0.698	0.748	0.826	0.914
V_{iR} (mV)	39.4	139.7	117.5	363.7	345.0	493.9	320.7	406.7

Table II. Practical Data Performed on a Solid Propellant Rocket Engine

	V_i (mV)							
Measuring time (s)	1	2	3	4	5	6	7	8
1	46.3	254.1	165.3	481.5	367.8	495.0	273.7	323.5
2	46.3	254.1	170.2	476.6	372.7	500.0	278.6	328.4
3	46.3	244.2	165.3	471.6	362.8	495.0	268.7	323.5
4	46.3	244.2	170.2	481.5	372.7	509.9	283.6	333.4
5	46.3	249.1	160.3	471.6	362.8	490.1	268.7	318.5
6	46.3	244.2	160.3	461.7	352.9	480.2	253.9	303.7
7	41.3	234.3	155.4	456.8	343.0	465.3	248.9	293.8
8	46.3	244.2	160.3	461.7	352.9	475.2	253.9	298.7
9	41.3	239.2	155.4	461.7	343.0	470.3	253.9	303.7
10	41.3	239.2	155.4	456.8	343.0	470.3	248.9	298.7
11	41.3	234.3	155.4	451.8	333.1	460.4	239.0	293.8
12	41.3	239.2	155.4	456.8	343.0	470.3	248.9	298.7

including the ignition initial condition and flameout ending condition, the practical recording time is 25 s.

To guarantee the measured state is in a combustion regime, we chose 12-group data starting from 6.5 s as the verifying data. So we can compare the experiment results with the theoretical results indicated by the rocket engine designer. See the 12-group data starting from 6.5 s in Table II [7].

According to the theoretical results indicated by the rocket engine designer, we know that the plume temperature of the rocket engine is within 2000–2600 K. So the initial temperature T_0 was chosen as 2200 K. Because the principal component of the rocket engine plume is Al_2O_3 and the spectral emissivity of Al_2O_3 is not high, the searching range of spectral emissivity is set to 0.1–0.65. See the experimental results in Table III.

4. UNCERTAINTY ANALYSIS

There are many factors that affect the uncertainty of the experimental results such as the pyrometer's performance, ground experiment arrangement, etc. Because high performance detectors and an amplifying circuit are used, the precision of the pyrometer is mainly affected by the calibration source, the calibration method based on the pyrometer wavelength function, and the A/D converter.

The effective emissivity of the calibration blackbody source is larger than 0.99. The temperature uncertainty is within ± 2 K. The uncertainty in the calibration method based on the pyrometer wavelength function is

Table III. Experimental Results for the Spectral Emissivity Data Performed on a Solid Propellant Rocket Engine

Measuring xstime (s)	T (K)	ε_1	ε_2	ε_3	ε_4	ε_5	ε_6	ε_7	ε_8
1	2504.1	0.409	0.649	0.520	0.506	0.425	0.416	0.375	0.369
2	2506.8	0.409	0.649	0.523	0.505	0.426	0.417	0.317	0.370
3	2498.4	0.416	0.634	0.529	0.504	0.427	0.425	0.376	0.377
4	2505.0	0.416	0.636	0.532	0.507	0.429	0.427	0.381	0.380
5	2499.9	0.409	0.647	0.517	0.504	0.424	0.416	0.374	0.367
6	2493.3	0.409	0.644	0.517	0.502	0.422	0.414	0.370	0.364
7	2482.3	0.408	0.629	0.523	0.501	0.422	0.419	0.369	0.367
8	2490.1	0.416	0.634	0.526	0.502	0.424	0.421	0.371	0.369
9	2485.3	0.408	0.631	0.523	0.502	0.422	0.420	0.371	0.371
10	2483.8	0.408	0.631	0.523	0.501	0.422	0.420	0.369	0.369
11	2481.3	0.403	0.640	0.515	0.501	0.417	0.411	0.365	0.361
12	2485.8	0.403	0.643	0.515	0.502	0.419	0.412	0.368	0.362

also within ±2 K [8]. The uncertainty in the A/D converter is less than 1 K because the temperature scale is 1500 to 3000 K and a 12-bit A/D converter was used. The uncertainty in the measurement distance resulting from the plume inflation is less than 1 K [7].

The total spectral temperature uncertainty of the pyrometer can be written as

$$e = \sqrt{e_1^2 + e_2^2 + e_3^2 + e_4^2} \tag{11}$$

where e is the total spectral temperature uncertainty of the pyrometer, e_1 is the uncertainty in the calibration source, e_2 is the uncertainty in the calibration method, e_3 is the uncertainty in the measurement distance, and e_4 is the uncertainty in the A/D converter.

5. DISCUSSION

(1) The theoretical true temperature of the engine flame near the nozzle exit indicated by the rocket engine designer is 2490.0 K. The difference between the calculated true temperature of the engine flame based on the algorithm presented in this paper and the theoretical true temperature of the engine flame indicated by the rocket engine designer is within ±20 K.

(2) The difference between the calculated true temperature of the engine flame based on Ref. 7 and the theoretical true tempera-

ture of the engine flame indicated by the rocket engine designer is within ±100 K.

(3) As for the estimated value of the first temperature, as long as the difference between the estimated value of the first temperature and the real true temperature of the first temperature is within ±200 K, the calculated results of the true temperature and spectral emissivities are in good agreement with the real true temperature and spectral emissivities of the measured target.

(4) As for the searching range of the spectral emissivity, the more narrow is the searching range of the spectral emissivity, the more precise are the calculated results of the true temperature and spectral emissivities.

(5) The processing method of multi-wavelength pyrometer data for continuous temperature measurements presented here cannot be applied to on-line data processing.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (No. 60377037) and the Scientific Research Foundation of Harbin Institute of Technology (Grant No. HIT. 2002. 18).

REFERENCES

1. J. L. Gradner, T. P. Jones, and M. R. Davies, *High Temp. High Press.* **13**:459 (1981).
2. A. Cezairliyan, *Temp., Its Measurement and Control in Science and Industry* **6**:757 (1993).
3. J. L. Gardner, *High Temp. High Press*. **12**:669 (1980).
4. P. B. Coates, *Metrologia*. **17**:103 (1981).
5. J. P. Hiernaut and R. Beukers. *High Temp. High Press.* **18**:617 (1986).
6. Xiao-Gang Sun, *J. Harbin Inst. Technol.* **5**:36 (1998).
7. Xiao-Dong Lu, *Ph.D. Thesis* (Harbin Institute of Technology, 1999).
8. Jing-Min Dai, *Acta Metrologica Sinica.* **20**:53 (1999).