

Presented at The 8th Symposium on Temperature: Its Measurement and Control in Science and Industry, October 21-24, 2002

The Spectropyrometer – a Practical Multi-wavelength Pyrometer

Ralph A. Felice

FAR Associates, 1532 Newport Drive, Macedonia, OH 44056, www.pyrometry.com

Abstract. An expert-system multi-wavelength pyrometer, commercially available since 1997 and using a spectrophotometer as its detector, has been able to overcome many well-known difficulties of pyrometry, including unknown, changing, and/or spectral dependence of emissivity as well as environmental absorption of radiation. In addition to a spectrophotometer and the usual optics, the instrument includes a computer which analyzes each measurement and then returns the temperature, the tolerance (a real-time measure of accuracy), and the signal strength (a quantity directly related to the emissivity at a chosen wavelength). The computer allows the input data, namely the thermal spectrum for each temperature measurement, to be saved. Accuracy to 0.10% is routinely achieved.

INTRODUCTION

Many multi-wavelength pyrometers have been proposed; a few examples are cited (1,2,3,4). An analysis of these and similar instruments concludes that accurate temperature determination cannot be made without knowledge of surface emissivity (5). Since emissivity can change with processing conditions, then clearly the only solution is to gain that knowledge while the temperature determination is being made.

The instrument described here, the Spectropyrometer, differs from other multi-wavelength pyrometers in that it is an expert system. It relies on no prior knowledge, but examines the data and makes decisions on how to process these data based on the results of tests that it applies. In addition to the temperature, the instrument displays both the tolerance and the signal strength for each measurement. The tolerance is a measure of the accuracy of the temperature determination. The signal strength is defined as the emissivity at a chosen wavelength as modified by the cleanliness of the optics and the fill factor of the field of view; it is calculated after the temperature.

Since the Spectropyrometer's introduction, more than 10,000 thermal spectra from various targets and processes have been analyzed. Absorptions of

extended portions of the visible and near-infrared spectra have been routinely detected in vessels with graphite as workpiece, furniture, susceptor, or barrier walls. Absorptions at 650 nm, a significant wavelength in pyrometry, appear to be the rule rather than the exception in such furnaces. Metallic behavior of emissivity, the monotonic decrease of emissivity with wavelength, is often seen in vacuum or inert gas furnaces with metal targets. Metals for which emissivity decreasing with wavelength has been observed include molybdenum, nickel, tantalum, titanium, tungsten, and zirconium. The Spectropyrometer detects and removes the absorptions from the thermal spectrum before calculation of temperature; it also detects and corrects for the monotonic decrease of emissivity with wavelength.

The Spectropyrometer is also insensitive to noise: 10% random noise introduces less than 1% uncertainty in the measured temperature. Another novel feature is that a radiation calibration is used because the instrument is based on a spectrophotometer. The device need only be calibrated at one well-known temperature (or with one well-known spectrum, as from a standard lamp). All subsequent temperatures are calculated relative to the known spectrum so the device is accurate throughout its range without extrapolation or interpolation. All temperatures are

therefore calculated from first principles. The instrument's narrow bandwidth and wide spectral ranges translate directly to broad thermal ranges of at least 1700°C for each model. Models using the visible and near-infrared (500 – 1000 nm) have been used from below 800 to above 3600°C; models sensitive in the infrared spectrum (1000 – 2200 nm) have been used down to 300°C. Agreement to within 0.10% with traceable standards is routine.

APPROACH

The mathematics for ratio pyrometry are well known. Solving Planck's law for temperature by dividing the intensities at two different wavelengths and making the usual short-wavelength-low-temperature assumption yields:

$$T_{12} = \frac{c_2(1/I_1 - 1/I_2)}{\ln R - 5 \ln(I_2/I_1)}. \quad (1)$$

Here T is the temperature, c_2 the second radiation constant, I the wavelength, and R the ratio of intensities at the two wavelengths. A straightforward way of doing multi-wavelength pyrometry would be to calculate all the possible T_{ij} for an ensemble of discrete wavelength/intensity pairs and average them. This works quite well for noise-free data collected on greybody or blackbody sources. To extend the usefulness of the technique to non-ideal targets an alternative approach has been adopted.

The spectral data are represented mathematically and selected wavelength/intensity pairs are used to calculate the corresponding temperatures. If the results are single-valued, as determined by the size of the standard deviation of this ensemble of temperatures, it indicates that the sample is a greybody and absorptions, if present, are not significant. The standard deviation is defined as the tolerance.

If the standard deviation of the temperatures calculated is large, it indicates one or more of the following conditions:

- emissivity is a function of wavelength;
- atmospheric absorptions are present;
- the temperature is not single-valued;
- the optical elements have changed characteristics.

The first two items can be detected and corrections can then be made. Unoxidized metals typically exhibit

emissivity that decreases monotonically with wavelength. It has been shown that a three-wavelength device can resolve temperature if the dependence of emissivity on wavelength is linear (6). With the multitude of wavelengths used by the Spectropyrometer, a correction that assumes emissivity can be represented by a linear function can easily be tried. Again, it is deemed successful if the result is single-valued, as judged by the size of the standard deviation.

Absorptions or emissions from process or intervening atmosphere or product offgas can also be detected by comparing the data spectrum with a thermal spectrum. Once detected, these spectral areas can then be removed from the calculation. Again, the agreement of the temperatures calculated from the remaining data indicates how well the temperature is known.

DESIGN AND APPARATUS

The Spectropyrometer is shown schematically in Figure 1. Wavelength separation and detection are provided by a grating spectrophotometer.

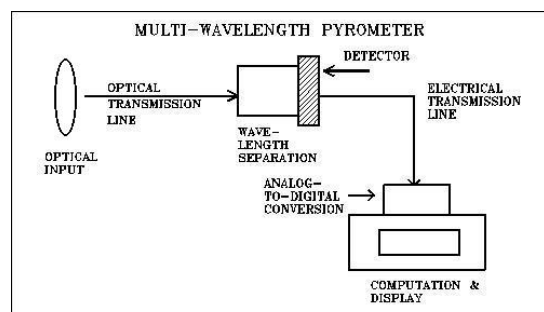


Figure 1. Schematic of the Spectropyrometer; from US Patents 5772323 and 6379038B.

The major requirement for the Spectropyrometer is that the detector array have a linear intensity response; an easy test for this is to compare the results from varying the exposure time while keeping the radiant intensity constant (7). Several spectrophotometers have been used successfully in this application; detectors have been photodiodes and CCDs. FAR currently uses two spectral ranges: 500 – 1000 nm and 1000 – 1700 nm; spectral resolution is 1 and 3 nm, respectively. The shorter-wavelength range has proved suitable for temperatures from around 800 to at least 4000°C, the longer-wavelength range for temperatures from 300 to 2000°C. Fiber optics are used with detectors of both ranges and have

interconnected these detectors to lenses, mirrors, and light pipes of commercial and custom manufacture.

An algorithm comprising an expert system to make the calculations and determinations discussed earlier has been rendered in software suitable for a desktop computer. The substantial amount of storage readily available on these devices makes it easy to store both raw spectra and processed results.

PERFORMANCE

The instruments described here have been commercially available from FAR Associates since 1997 and in limited use and development since 1987. Consequently, a great deal of data has been collected and analyzed. These analyses have demonstrated accurate performance despite emissivity changes, atmospheric interference, and random noise.

Emissivity Changing With Wavelength

The monotonic decrease of emissivity with wavelength has been detected in several metals (Mo, Ni, Ta, Ti, W, Zi) and in metal carbide coatings on ceramic substrates. Most metals have been observed to behave similarly (8).

The change of emissivity with wavelength can induce large errors in ratio pyrometers. Figure 2 shows the temperatures that straightforward ratio pyrometry calculations would yield on the data collected from a coiled-coil tungsten halogen lamp by a spectrophotometer. The temperatures calculated from the raw data (the jagged line) and the mathematical representation (the smooth line) are plotted against the average of the two wavelengths used for the ratio calculation.

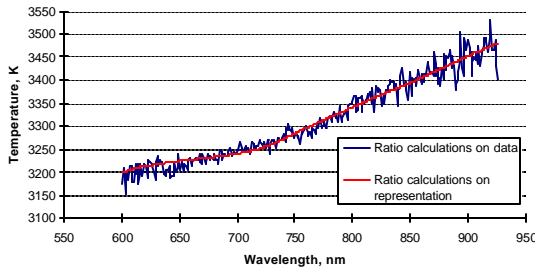


Figure 2. Results of ratio pyrometry calculations on a tungsten target. Uncertainty is greater than 300 °C.

Figure 3 shows the results of calculations performed by the Spectropyrometer on the same data. It can be seen that the indeterminacy of Figure 2 has been replaced with a single value: the average is 3058 Kelvins, with a standard deviation of 4.9K.

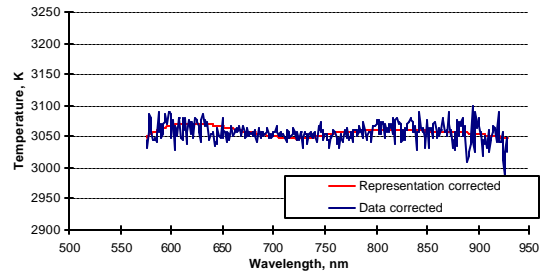


Figure 3. Spectropyrometer's results on a tungsten target.

The spectral emissivity can now be calculated from the raw data (the thermal spectrum) and the measured temperature. The results of such a calculation are shown in Figure 4, along with published data for tungsten (9).

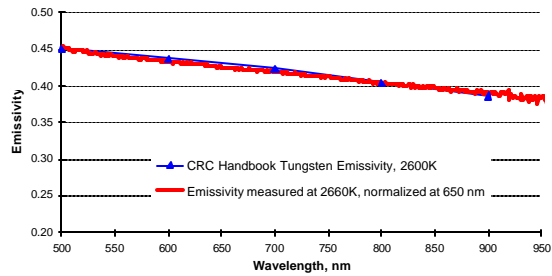


Figure 4. Emissivity calculated as described above, plotted with and normalized to data taken from the CRC Handbook.

The monotonic decrease of emissivity with wavelength in metals, while common, is not universal. Surprisingly small changes in composition have been seen to affect the emissivity greatly. The following measurements were made on rods of pressed tantalum powder sintered in vacuum. The proprietary compositions differed by only a few atomic percent of alloying materials. Nonetheless, one behaved as a greybody, the other as a metal with emissivity being a function of wavelength. Figure 5 shows the results.

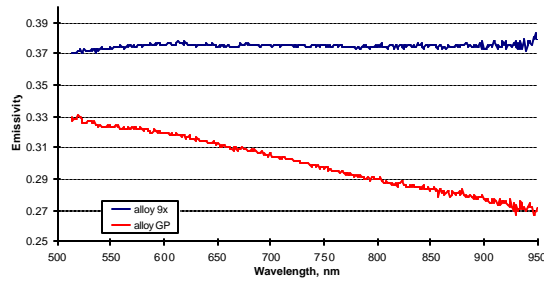


Figure 5. Tantalum metal exhibiting both greybody (alloy 9x) and colorful behavior (alloy GP).

A material’s emissivity behavior is known to depend on the surface morphology. A molybdenum target with two surface modifications was spatially scanned using the Spectropyrometer. The modified surfaces consisted of a light surface knurling and a square-bottomed channel, 1.2 times as deep as its width. The scan used a spot size half the width of the modifications. The scan made several measurements down the length of the modifications, and included a length of unmodified material. Both modified surfaces were more efficient radiators than the unmodified material, but all exhibited the monotonic decrease in emissivity with wavelength associated with metals.

Despite the emissivity for the three surfaces varying from 12% to 25% over the wavelength range of the Spectropyrometer, the temperatures returned for the three regions agreed very well: $1451 \pm 3.1^\circ\text{C}$ in the channel, $1455 \pm 3.5^\circ\text{C}$ for the knurled surface, and $1450 \pm 3.0^\circ\text{C}$ for the unmodified surface.

A check of consistency of the Spectropyrometer’s performance on metal targets was done with a tungsten lamp as the target and two Spectropyrometers of different wavelength ranges. To ensure the same target for both instruments, a single lens and fiberoptic were alternated between the two Spectropyrometers. Current to the lamp was varied from 35% – 70% of the design current, such that the temperature was in range for both pyrometers. Results are shown in Table 1. The average agreement is to within $\pm 0.22\%$.

TABLE 1. Tungsten results for Spectropyrometers of different wavelength ranges.

Lamp Current, %	Temp., °C (vis & NIR)	Temp., °C (IR)
35	1162	1146
44	1444	1434
55	1601	1603
62	1768	1766
67	1899	1900
70	2037	2022

Materials with ceramic coatings are of great technological interest, so a metal carbide-coated graphite sample was the target for measurement of emissivity at elevated temperatures. The sample was placed in a horizontal tube furnace, open on the end that faced the sample coating, and purged with argon from the closed end. A sliding sight tube, also purged, was rigidly attached to a lens assembly which was connected to the Spectropyrometer by a fiberoptic. The optical input of the sight tube was placed just inside the open end of the tube furnace. While the furnace was heated to the desired setpoint the Spectropyrometer monitored the temperature and reported greybody behavior; the furnace sensor and the Spectropyrometer agreed during this period. When the setpoint was reached, the sight tube was plunged into the furnace to within 1 millimeter of the target surface to eliminate sidewall radiation. Data collected during the plunge showed greybody behavior until the close approach to the target, where the emissivity was seen to have a spectral dependence, as shown in Figure 6. The temperature detected at the target surface was consistent with the temperatures returned by the Spectropyrometer before and after the plunge. Of interest here is the automatic detection of the change of emissivity from grey to wavelength-dependent as the sidewall radiation was eliminated, and the agreement of the temperatures for both cases.

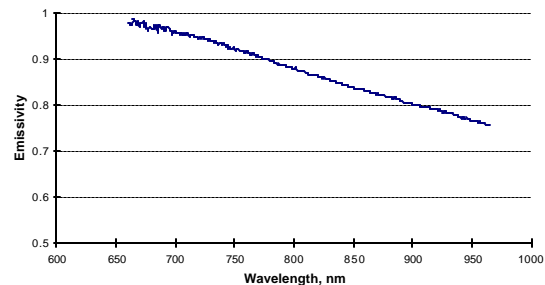


Figure 6. Emissivity of a metal carbide coating at 1175°C ; the probe cooled the target from the furnace temperature of 1200°C .

Atmospheric Absorption and Emission

Substantial gaseous absorptions have been observed in many applications, especially those with graphite as either workpiece or refractory. Figure 7 is a graph of both the spectrum of a carbonaceous workpiece undergoing graphitization and Planck’s curve for the detected temperature.

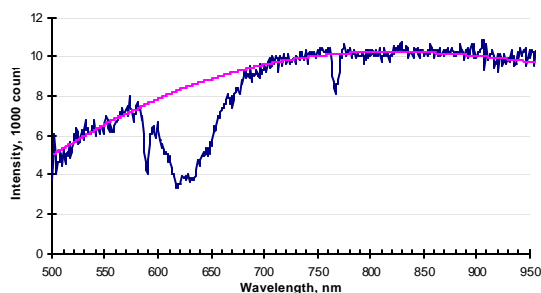


Figure 7. Thermal spectrum with Planck's curve for the measured temperature, 3253°C, superimposed.

Immediately after this measurement, the target area's inert gas purge was increased. Figure 8 shows the corresponding spectra. Note that the "before" and "after" temperatures are within 7°C of each other, with the temperature measured during increased purging being cooler, as expected.

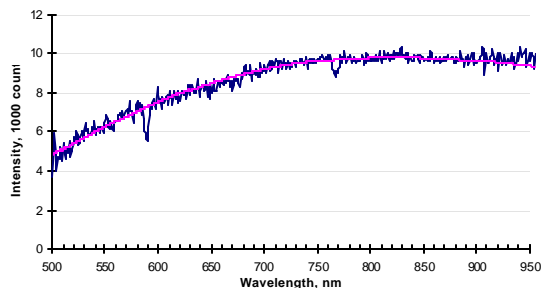


Figure 8. Thermal spectrum of same conditions as Figure 7, but after purge; temperature is 3246°C.

Prior to the increased purge, under the conditions of Figure 7, measurements were made with a vanishing filament pyrometer; it returned 2800°C, a difference of 450°C. Obviously, a conventional pyrometer with sensitivity anywhere in the affected area of the spectrum would also have been incorrect.

Emissions have also been detected, particularly in vessels with exposed electrical conductors. Figure 9 shows an absorption/emission spectrum from the hot isostatic pressing of a ceramic material. It was calculated by subtracting the data spectrum from the normalized Planck's law curve for the temperature returned by the Spectropyrometer. The spectral area from 600 to about 740 nm shows the emission, which is attributed to gaseous species glowing due to a parasitic electrical path through the process atmosphere. Increasing process gas flow while maintaining the same pressure in the vessel reduced the gas's conductivity and flipped the emissions back to absorptions.

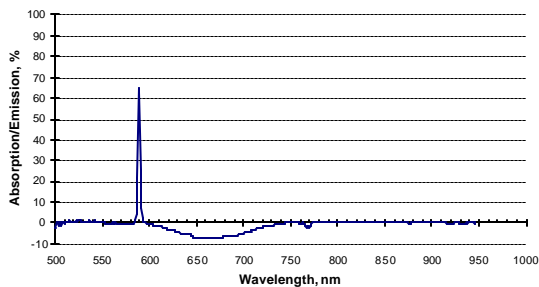


Figure 9. Difference between data spectrum and normalized Planck's law temperature spectrum; negative values indicate emissions.

Graphs such as Figure 9 have been used to identify the species present in the process atmosphere.

Noise

Others (10) have reported 5% uncertainty in temperature with 1% noise in the thermal spectrum. The Spectropyrometer shows very different results. Because the entire spectrum contributes to generating the best thermal curve possible, the effects of noise are minimized. To illustrate, theoretical thermal spectra were generated for a wide range of temperatures. Random noise of 5% and 10% magnitude were added to the spectra, which were then processed by the Spectropyrometer as if they were data the instrument had collected. The results given in Table 2 show a maximum difference of less than 0.6% from the true temperature and an average difference of 0.16%.

TABLE 2. Spectropyrometer results on data with added noise; tolerance defines 100% confidence interval.

Temperature, °C	Output with 5% noise, °C	Output with 10% noise, °C
1000	1001.6 ± 8.1	1001.8 ± 12.7
1400	1400.4 ± 6.6	1402.9 ± 6.7
1800	1799.1 ± 6.7	1801.8 ± 13.3
2200	2201.6 ± 2.8	2194.8 ± 17.2
2600	2600.6 ± 5.6	2607.3 ± 24.2
3000	3004.5 ± 8.4	2980.5 ± 31.6

A thermal spectrum from an industrial process, already fairly noisy in appearance, was modified with 10% random noise and is shown as Figure 10. The temperature returned from the noisy data differed by 13°C (0.4%) from the original. The tolerance, the standard deviation of the temperature calculation, increased by 13°C, giving an immediate indication of the increased uncertainty.

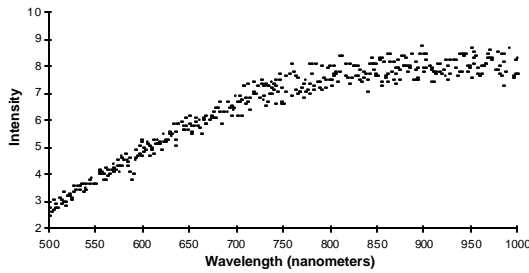


Figure 10. Data collected in an industrial environment with 10% noise added. Before the addition, temperature was returned as $2887.0 \pm 10.3^\circ\text{C}$, after the addition the value was $2899.7 \pm 23.2^\circ\text{C}$.

These extreme examples show that noise is not a problem with the Spectropyrometer.

CALIBRATION

Calibration of the Spectropyrometer is very straightforward, requiring only a single, well-known spectrum from a blackbody or a standard lamp. The known spectrum should be such that all the elements of the detector array are illuminated sufficiently that they are in their linear regime. Table 3 shows a typical calibration; the standard was a Luxtron M100 pyrometer. Average uncertainty is seen to be $\pm 0.043\%$.

TABLE 3. Typical calibration results; source was an Electro Optical Industries BWS156 blackbody.

NIST-traceable standard, $^\circ\text{C}$	Spectropyrometer, $^\circ\text{C}$	D/T $\pm\%$ absolute
995.5	996.0	0.020
1198.1	1200.9	0.095
1492.1	1493.5	0.040
1982.6	1983.5	0.020
2184.0	2182.0	0.041

The calibration itself is the same as the intensity calibration for any spectrophotometer: wavelength-by-wavelength division of the known spectrum of the source by the spectrum returned by the instrument generates the correction array. Disagreement between source and instrument calibrated in this manner has regularly been seen to be smaller than that expected from the error expression of ratio pyrometry:

$$\frac{dT}{T} = \frac{T}{c_2} \left(\frac{I_1 \times I_2}{I_1 - I_2} \right) \frac{dR}{R} \quad (2)$$

where T is the absolute temperature, R the ratio, c_2 the second radiation constant, and I_1 and I_2 are taken as

the extremes of the Spectropyrometer's useful wavelength range. This equation also points out the advantage of a radiation calibration. The quantity modifying dR/R is substantially less than unity for much of the Spectropyrometer's range; for example, a radiation calibration with a 1% uncertainty corresponds to a temperature calibration with an uncertainty of 0.25% at 2000°C for a silicon instrument.

CONCLUSIONS

An expert system multi-wavelength pyrometer, the Spectropyrometer, has been successful in many industrial processes. These include metal, ceramic, and engineered-materials manufacture and processing. It has returned consistent temperatures despite changing emissivity and atmospheric absorptions and emissions. It requires no prior knowledge of the target or the environment. In addition to the temperature, the instrument returns the tolerance, a real-time measure of the temperature determination's accuracy. Further, thermal spectra are stored and can be analyzed for more information, including species present in the process atmosphere. For targets with changing emissivity and/or substantial noise the maximum uncertainty is typically below 0.75%. Where the temperature is well known and the source well behaved (greybody sources), the Spectropyrometer achieves a maximum uncertainty of less than 0.1%.

REFERENCES

1. Ruffino, G., Zaixiang, C., Sjoggaog, K., and Jingmin, D., "Multiwavelength pyrometer with photodiode array" in *Temperature its Measurement and Control In Science and Industry*, Vol. 6, edited by J. F. Schooley, AIP, New York, 1993, pp. 807-811.
2. Gardner, J.L., Jones, T.P., and Davies, M.R., "A Six Wavelength Radiation Pyrometer", *High Temperatures-High Pressures*, Vol. 13, 459-466 (1981).
3. Hunter, G. B., Allemand, C.D., and Eagar, T.W., *Optical Engineering* Vol 25, no.6, 1081-1085 (1985).
4. Cezairliyan, A., Foley, G. M., Morse, M.S., and Miiller, A. P., "Six-wavelength millisecond-resolution pyrometer" in *Temperature its Measurement and Control In Science and Industry*, Vol. 6, edited by J. F. Schooley, AIP, New York, 1993, pp. 757-762.
5. Neuer, G., Fiessler, L., Groll, M., and Schreiber, E., "Critical analysis of the different methods of multiwavelength pyrometry" in *Temperature its*

Measurement and Control In Science and Industry,
Vol. 6, edited by J. F. Schooley, AIP, New York, 1993,
pp. 787-790.

6. Hornbeck, G. A., "High Speed Ratio Pyrometer",
*Temperature its Measurement and Control In Science
and Industry*, Vol. 3, edited by C.M. Herzfeld, Reinhold,
New York, 1962, pp. 425-428.
7. Ronchi, C., Sheindlin. M., *International Journal of
Thermophysics* **23**(1): 293-305 (2002).
8. Touloukian., Y. S. and DeWitt, D. P., *Thermophysical
Properties of Matter, Vol. 7: Thermal Radiative
Properties*, New York: IFI/Plenum, 1970.
9. Weast, R. C., *CRC Handbook of Chemistry and
Physics, 60th Edition*, Boca Raton: CRC Press Inc., 1980,
pp. E-381, E-394.
10. Andreic, C., *Appl. Optics* **27**, no. 19, 4073-4075 (1988).