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Spectral stray light effect on high-temperature measurements using a near-infrared multi-wavelength pyrometer

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HIGHLIGHTS

- Spectral stray light is corrected for multi-wavelength pyrometer using a laser.
- Corrections for spectral stray light improve the accuracy of optical pyrometer.
- Simplified temperature calibration procedure for optical pyrometer is given.
- Measurement accuracy of calibrated pyrometer is experimentally verified.

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ABSTRACT

The spectral stray light is a major, non-negligible error source affecting spectral intensity measurements for optical instruments. The purpose of this study is to investigate the effects of spectral stray light on high-temperature measurements using a near-infrared (1.0–1.65 μm) multi-wavelength pyrometer. The spectral stray light corrections were measured for the multi-wavelength pyrometer using a pulsed tunable laser for wavelengths from 0.41 μm to 2.63 μm. A matrix correction method was then used for the spectral stray light for the multi-wavelength pyrometer. The spectral response characteristics of the pyrometer were calibrated using a standard high-temperature blackbody source. The experimental results show that the spectral response characteristics are approximately identical for different calibration temperatures when the spectral stray light correction is used. The corrections for the spectral stray light significantly improve the accuracy of the multi-wavelength pyrometer at a blackbody calibration temperature which gives a simplified accurate calibration procedure, unlike the temperature calibrations for general optical pyrometers. Temperature measurement tests using a multi-wavelength pyrometer for standard high-temperature source further verified the measurement accuracy of the calibrated pyrometer which also illustrates the necessity of the spectral stray light corrections for the complex optical pyrometer and the applicability of the multi-wavelength algorithm.

1. Introduction

Non-contact optical measurements of high temperature objects are of great importance in many research and industrial applications [1–6]. Optical pyrometry based on one-color or two-color measurements in different spectral regions is well developed and commonly used to determine surface or volume temperatures. Fat'yanov et al. [1] developed a time-resolved two-band infrared pyrometer to measure temperatures of carbon tetrachloride during shock compression. Benedic et al. [4] used two-color pyrometry with a multiple layer and effective media approximation model for real-time monitoring of thin film growth.

Although traditional optical pyrometry is an attractive method that is widely used for monitoring temperatures, the method still faces the intrinsic difficulty that the unknown emissivity of the object is not that of an ideal blackbody which results in temperature measurement errors. As an improvement over one-color or two-color pyrometry, multi-wavelength pyrometry has been used to determine temperatures from spectral intensity measurements at different wavelengths [7–26]. More measurement information greatly reduces the effect of the uncertainty in the spectral emissivity. Ng and Fralick [10] used a multi-wavelength pyrometer for temperature measurements of thermal barrier coatings, glass

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materials, and combustion gases. Katzir et al. [12,13] developed four-band and multi-band fiber-optic radiometers for gray body temperature measurements at 5–20 μm. Madura et al. [14] propose a method of correction of remote measurements of seawater surface temperature using multispectral IR pyrometer. Simmons et al. [16] measured the temperatures of cathodes using multispectral imaging with a conventional CCD camera and a spot pyrometry. Duvaut [19] reviewed the theoretical developments and research status of multi-wavelength pyrometry and compared experimental results obtained in the visible and middle infrared spectral ranges. Fu et al. [21–24] used multicolor pyrometers with various algorithms to determine the temperatures of diesel combustion flame, hot surface and semi-transparent infrared material at various experimental environments. Kappagantula et al. [25] measured the spatial temperature distribution of combustion products using a multi-wavelength pyrometer and an infrared camera. Estevadeordal et al. [26] used a high-speed multicolor pyrometry to measure radiation temperatures of hot particulate bursts generated from a combustor at certain engine conditions.

Unlike the traditional one-color and two-color ratio pyrometers, the multi-wavelength pyrometer is not yet commercially available and is not widely applied in research and industrial settings. The limited usage arises from the complex instrument design and the algorithm uncertainty. Although multiple spectral signals can provide sufficient measurement information to theoretically deduce an accurate temperature solution, the method introduces more uncertainty sources related to the multiple variables from the optical measurement system for the uncertainty analysis. Spectral dispersion is obtained by means of dispersion prisms, optical gratings and interference filters in the multi-wavelength pyrometer design. A key measurement uncertainty with multi-wavelength pyrometers is the unwanted spectral stray light that is projected on the pyrometer sensor. Spectral stray light was the dominant stray light in many applications of optical instruments. Spectral stray light generally originates from radiation scattered from imperfections in the dispersing grating, filter, prism and other optical elements in the system and can cause larger errors when measuring the spectral intensities of a source with a broad-band radiation distribution. The analysis of spectral stray light has been of great concern for spectrometer applications in the fields of colorimetry, photometry and optical spectroscopy with some correction methods developed to reduce the effect of the spectral stray light [27–38].

However, few studies have focused on analyzing the effect of spectral stray light for temperature measurements using a multi-wavelength pyrometer even though the need for optical pyrometers is rapidly increasing for actual applications. The accuracy of the multi-wavelength pyrometer itself has greatly restricted commercial and scientific applications. For spectral measurements, spectral stray light is one of the main error sources affecting the pyrometer instrument accuracy although it is usually ignored and difficult to quantify. The purpose of this paper is to investigate the spectral stray light effect for temperature measurements using a near-infrared (1.0–1.65 μm) multi-wavelength pyrometer. The measurements of the spectral stray light correction for this multi-wavelength pyrometer use a pulsed tunable laser with a spectral range of 0.41–2.63 μm. A matrix correction method is used to correct the spectral stray light for this near-infrared pyrometer. The spectral response characteristics of the pyrometer are calibrated using a standard high-temperature blackbody source with corrections for the spectral stray light. Finally, the measurements of a standard high-temperature source using the multi-wavelength pyrometer verify the measurement accuracy of the calibrated optical pyrometer. The analyses provide valuable insight for applications of multi-wavelength pyrometry in research and industrial fields.

2. Multi-wavelength pyrometry

Multi-wavelength pyrometry analyzes spectral radiation intensity measurements at various wavelengths. For accurate temperature measurements of actual objects, the analysis must include a spectral emissivity model for the pyrometer. The temperature and emissivity can be determined using different algorithms through multiple spectral intensity signals and the specified emissivity model. When the spectral signals are accurate, the temperature measurement accuracy of the multi-wavelength pyrometer mainly depends on the emissivity model, wavelength choices and solution algorithms.

The spectral radiation intensity, I_{λ_i}, of the actual object at wavelength λ_i obtained by a multi-wavelength pyrometer is given by:

$$I_{\lambda_i} = \varepsilon(\lambda_i, T) I_b(\lambda_i, T), \quad i = 1 \ldots N \tag{1}$$

where T is the temperature, ε is the spectral emissivity, I_b is the spectral radiation intensity distribution of an ideal blackbody at the same temperature, i is the index of the wavelength channel and N is channel number for the multi-wavelength pyrometer. The spectral emissivity can be modeled with simple functions (constant, linear, polynomial, exponent, etc.) for the spectra region j with narrow wavelength bandwidth $(\lambda_{j,\min}, \lambda_{j,\max})$. The example of a linear emissivity model is:

$$\varepsilon_j(\lambda) = a_{j,0} + a_{j,1}\lambda, \quad \lambda \in (\lambda_{j,\min}, \lambda_{j,\max}) \tag{2}$$

where $a_{j,0}$ and $a_{j,1}$ are the parameters describing the emissivity characteristics. The spectral range of the multi-wavelength pyrometer with N measurement wavelengths is divided into M spectral sub-regions. The emissivity of the object in each spectral sub-region can then be characterized by the linear model with two unknown parameters, $a_{j,0}$ and $a_{j,1}$. The least squares method or other algorithms can then be used to solve for the temperature and spectral emissivity by minimizing the error function, ψ,

$$\psi = \sum_{i=1}^{N} \left(I_{\lambda_i,meas} - \varepsilon_j(\lambda_i) I_{\lambda_i,b}\right)^2, \quad j = 1 \ldots M \tag{3}$$

This is the basic principle of multi-wavelength pyrometry as has been discussed previously.

A near-infrared multi-wavelength pyrometer with a spectral response of 1.0–1.65 μm was used as an upgrade over traditional one-color or two-color pyrometer. The near-infrared spectra are suitable for high-temperature measurements. The near-infrared radiance intensity is more sensitive than the far-infrared radiance intensity for high-temperature measurements. Also, the near-infrared spectra have excellent response sensitivity to low intensity signals compared to short visible spectra. The sensor of the multi-wavelength pyrometer was a 256 pixel InGaAs array detector with an effective response range of 1.0–1.65 μm. The wavelengths separation was realized by dispersion gratings with the common Czerny–Turner design. The InGaAs detector acquires an entire spectral image within 1.0–1.65 μm spectral range in one scan. The optical elements included a near-infrared optics lens, an entrance slit, a diffraction grating and mirrors. The light entered the optical bench through the near-infrared optical lens with an effective focus length of 91 mm and was collimated by a spherical mirror. A plane grating diffracted the collimated light with the resulting diffracted light focused by a second spherical mirror. An image of the spectrum was projected onto the InGaAs detector array to enable fast scanning of the spectrum. The maximum sampling frequency for the spectral images was 2 kHz. The pyrometer working distance was from 0.6 m to infinity. The space resolution of the object was 2 mm at a distance of 1 m. The pyrometer had a total of 175 spectral channels with 4 nm wavelength intervals, which provided a high spectrum resolution measurement