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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:

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

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:

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

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 capability compared to other optical pyrometers. The broad spectral response range and high spectrum resolution of this multi-wavelength pyrometer gave sufficient measurement choices for various samples, experimental conditions and temperature ranges. In applications of multi-wavelength pyrometry, continuous spectral wavelengths may be integrated into a series of measurement wavebands with perhaps a 50 nm bandwidth to increase the signal intensity and reduce the effect of signal fluctuations at discrete wavelengths. The interference arising from the environmental radiation absorption and emission need to be separated from the measurements and eliminated in the integration process for the multi-wavelength pyrometry analysis.

3. Experimental apparatus for spectral stray light correction

Although multi-wavelength pyrometers have some advantages due to the InGaAs detector array and the dispersion grating, applications of multi-wavelength pyrometers are still restricted by the measurement uncertainty, especially the uncertainty in the spectral intensity measurements. The measurement uncertainties of the spectral signals for the multi-wavelength pyrometer are larger than those for the spectral signals of traditional scanning spectrometers. The grating-array detector design in the multi-wavelength pyrometer can result in non-negligible background signals, called spectral stray light, originating from scattered radiation from imperfections in the dispersion grating and other optical elements in the pyrometer system. The spectral stray light projected on the pyrometer sensor is not very intense, on the order of 10^{-4} of the spectral irradiation intensity. However, the sum of the radiation reflected from all wavelengths to one wavelength, especially when the real signal is weak, can be large enough to cause large errors [27–29]. The multi-wavelength pyrometer is generally calibrated for the wavelength response, nonlinearity intensity response and temperature response characteristics against a standard high-temperature blackbody source and a standard HgAr lamp source before the pyrometer is used. The effect of the spectral stray light can be significant when the spectral intensity distribution of the measured object differs from the spectral distribution of the calibration source for the multi-wavelength pyrometer. In such conditions, the spectral intensity measurement errors arising from the spectral stray light are intrinsic and are sometimes the dominant pyrometer measurement error.

The effects of the spectral stray light on the temperature measurements using the near-infrared multi-wavelength pyrometer were evaluated using the measurements of spectral stray light correction. The calibration facility shown in Fig. 1 included a pulsed tunable laser source with a 0.41–2.63 μm spectral range. This laser is quite useful for measurements of the spectral stray light effect due to its narrow spectral bandwidth, its high power density in the narrow bandwidth, its easily tunable wavelength, and its large tunable wavelength range. A laser pulse from a Lab170-10 Nd:YAG laser generated a UV laser pulse at 0.355 μm which was fed to an Optical Parametric Oscillator (OPO, PremiScan/240/MB-ULD) to pump the so called parametric down conversion. Therefore, two laser beams are generated by the OPO, one named the signal and the other the idle due to the nonlinear optics, and could be distinguished by their polarization and wavelength. The total energy of the signal pulse plus the idle pulse was equal to the incident pumping beam, which was about 3.5 eV corresponding to its 0.355 μm wavelength. Therefore, if the signal beam was adjusted to 0.55 μm, or 2.3 eV per pulse, the idle beam would be 1.0 μm, or 1.2 eV per pulse to keep the total energy per pulse equal to 3.5 eV. The signal beam, whose wavelength was adjusted to be in the range of 1.0–1.65 μm, was used. The corresponding idle beam with wavelengths from 0.452 μm to 0.55 μm, was absorbed by a long pass filter near the OPO output. The signal beam then passed through a set of removable neutral density filters to adjust its power. A diaphragm was inserted in the optical path to block possible environmental radiation other than the signal beam from entering the integration sphere. The integration sphere made the light beam uniform before entering the pyrometer as shown in Fig. 1.

The spectral stray light into the multi-wavelength pyrometer was characterized by measuring the monochromatic laser spectral line. The signal response measured by the pyrometer sensor outside of the specified laser spectral line was assumed to originate from spectral stray light. Therefore, the spectral stray light distribution was determined by measuring the response to a series of laser spectral lines over the pyrometer's spectral range using the tunable laser source. The experiments used a total of 14 laser lines with wavelengths spaced every 50 nm which is about 13 pixels for the pyrometer wavelength range. The relative spectral responses of the pyrometer to several representative laser light lines (1.05 μm, 1.20 μm, 1.35 μm, 1.50 μm and 1.65 μm) are shown in Fig. 2. The responses illustrate that the original relative spectral stray light signals are approximately 1×10^{-4}–5×10^{-4} of the maximum for wavelengths from the center wavelength of the laser line. The non-iterative matrix multiplication method proposed by Zong et al. [29] was used. This method uses a spectral line spread function (LSF) and a stray light distribution function (SDF) for real-time corrections of spectral stray light. The corrected spectral response of the multi-wavelength pyrometer was determined using the matrix multiplication based on the square SDF matrix.

4. Results and discussions

4.1. Spectral response calibration

General optical pyrometers such as one-color and two-color pyrometers need to be calibrated against a standard blackbody source to relate the pyrometer output data (one channel for a one-color pyrometer or the ratio of two channel signals for the two-color pyrometer) and the blackbody source temperature. The nominal temperature range of optical pyrometers is then based

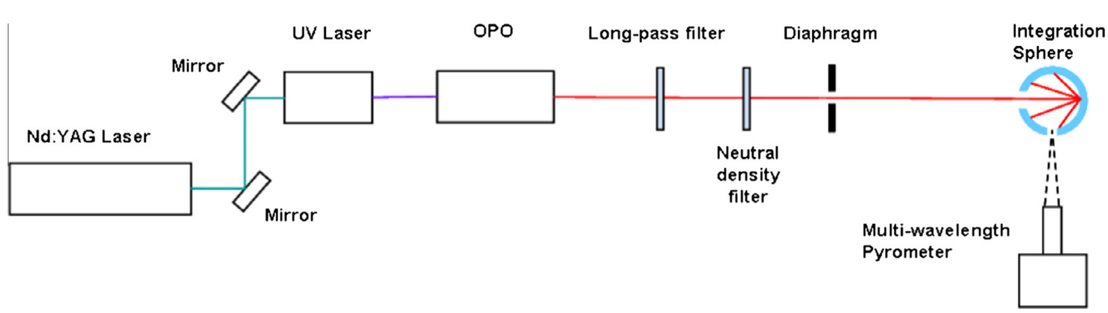

Fig. 1. A pulsed tunable laser optical setup for the spectral stray light measurements.

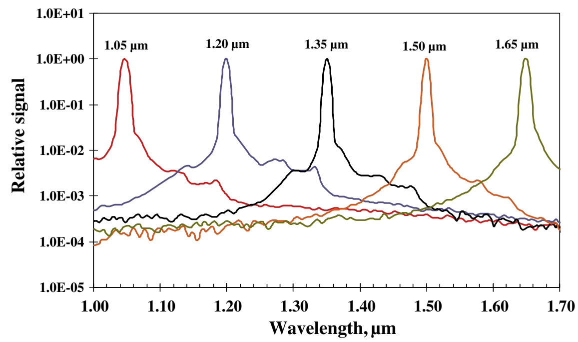

Fig. 2. Relative spectral signals of the pyrometer for 1.05 µm, 1.20 µm, 1.35 µm, 1.50 µm and 1.65 µm laser light lines.

on the blackbody temperatures. However, for a multi-wavelength pyrometer, one blackbody calibration temperature corresponds to multiple channels of output data which makes the calibration procedure significantly different. The multi-wavelength pyrometry data analysis described by Eqs. (1)–(3) directly depends on the spectral radiation intensities in the multi-channel output data. Therefore, the purpose of the pyrometer calibration is to obtain the spectral radiation intensities at the working wavelengths from the original measured output data. The temperature calibration for a multi-wavelength pyrometer is converted to the calibration of the spectral radiation intensity which is the spectral response characteristics at various wavelengths. The standard blackbody source provides a traceable, accurate spectral radiation intensity distribution at the blackbody temperature.

The wavelength response and the non-linear intensity response of the multi-wavelength pyrometer are traditionally calibrated using a standard HgAr light source as reported in the literature [22] and are not repeated here. The spectral radiation intensity can be derived from the pyrometer output signal:

$$I_\lambda = (V_\lambda - V_{\lambda,noise})/(F_1 F_2) \tag{4}$$

where F_1 is the nonlinear intensity response function which can be described by the polynomial model obtained using the standard HgAr light source, F_2 is the spectral response function, V_λ is the original output signal value, and $V_{\lambda,noise}$ is the output value for dark noise. The pyrometer spectral response function, F_2, is determined using the standard blackbody source. The spectral response function of the multi-wavelength pyrometer is an intrinsic instrument property that remains unchanged if all the optical components are fixed and should be independent, theoretically, of the calibration source parameters, for example, the temperature of the standard blackbody calibration source.

The calibration results for the spectral response representing by F_2 at the various blackbody temperatures (1090.5 °C, 1197.8 °C, 1295.4 °C, 1404.0 °C) are shown in Fig. 3 without the spectral stray light corrections. The percentages differences in the spectral response at 1197.8 °C, 1295.4 °C and 1404.0 °C relative to the baseline are shown in Fig. 4 where the curve at 1090.5 °C in Fig. 3 is used as the baseline. The differences among the calibration curves at different temperatures mostly arise from the effects of the spectral stray light. The relative differences greatly increase as the difference between the blackbody calibration temperature and the baseline blackbody calibration temperature increases. For example, the relative difference of the spectral response of 1150.1 nm reaches 4.08% between 1090.5 °C and 1404.0 °C. Wavelength channels with weak measurement signals are more inclined to be affected by the stray light. For this reason, the relative differences in the spectral response are significantly larger at shorter wavelengths than at longer wavelengths. At 1.401 µm where the signal is strong, the maximum relative difference is 0.3%, while the maximum is 7.7% at 1.001 µm.

The corrected spectral responses of the multi-wavelength pyrometer can then be obtained from the spectral stray light corrections as described in Section 3 using the correction matrix method proposed by Zong et al. [29]. These corrected spectral responses at different calibration temperatures match very well. The differences in the spectral response at 1197.8 °C, 1295.4 °C and 1404.0 °C relative to the spectral response curve at 1090.5 °C that are shown in Fig. 5 are very small and only within 0.3% for the 1.10–1.65 µm wavelengths. Therefore, the pyrometer spectral response calibration will be accurate at one temperature condition once the spectral stray light correction is quantified, and is not over the entire temperature range. The corrected spectral response representing by F_2 is suitable for accurate measurements of the spectral radiation intensity based on Eq. (3) even when the spectral distribution of the object differs significantly from that of the calibrated blackbody source. The analysis shows that the spectral stray light corrections guarantee the calculation accuracy of the multi-wavelength pyrometer at the blackbody temperature which provides a clear and simplified calibration procedure that is not the same as the temperature calibrations for general optical pyrometers.

4.2. Temperature measurement verification

The calibrated near-infrared multi-wavelength pyrometer was used to measure the temperatures of high-temperature objects to verify the temperature measurement accuracy. The effects of the spectral stray light in the multi-wavelength pyrometer can cause significant errors in the spectral response function and affect the

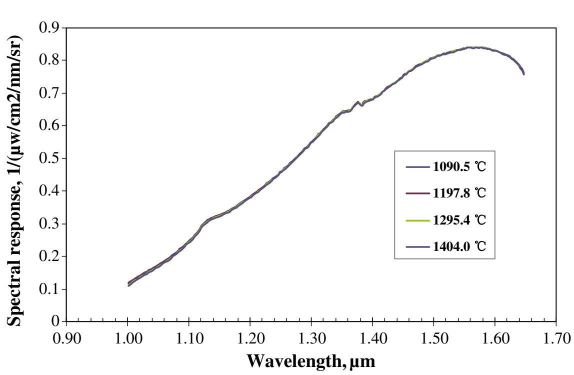

Fig. 3. Spectral response distributions at blackbody temperatures of 1090.5 °C, 1197.8 °C, 1295.4 °C and 1404.0 °C (without the spectral stray light corrections).

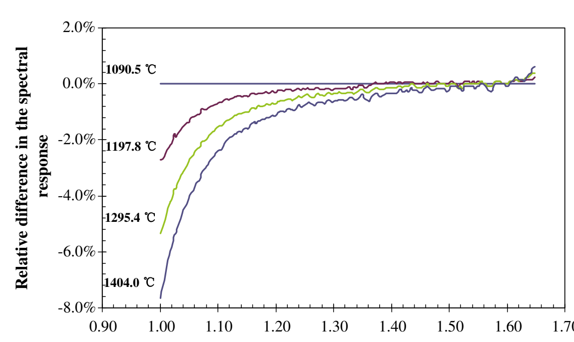

Fig. 4. Relative differences in the spectral responses at 1197.8 °C, 1295.4 °C and 1404.0 °C relative to the baseline at 1090.5 °C (without the spectral stray light corrections).

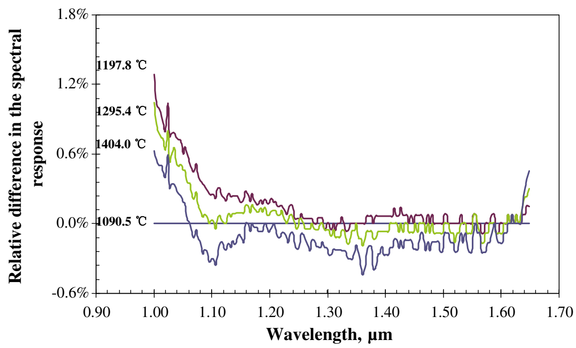

Fig. 5. Relative differences in the spectral response at 1197.8 °C, 1295.4 °C and 1404.0 °C relative to the baseline at 1090.5 °C (considering the spectral stray light corrections).

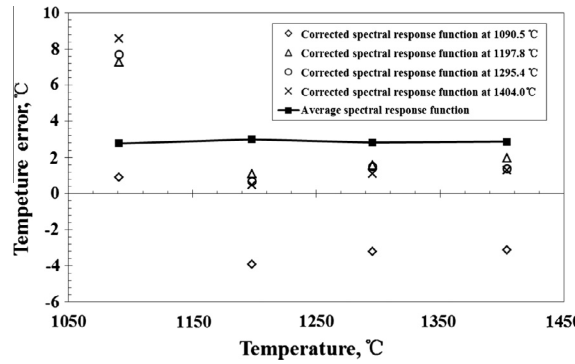

Fig. 7. Temperature errors using the corrected spectral response curves obtained at different calibration temperatures with stray light corrections.

measured spectral radiation intensities at different wavelengths. Thus, the evaluations of the temperature measurement accuracy for the multi-wavelength pyrometer will consider two error sources:

A. Inaccurate multi-channel spectral intensities will produce errors based on Eq. (1). The objective of spectral stray light analysis was to reduce the measurement uncertainties of the multi-channel spectral intensities.
B. The solution algorithm for the multi-channel intensities measured by the multi-wavelength pyrometer is another error source even though the measured intensities are accurate due to the unknown emissivities in real measurements.

The experiments to verify the measurement accuracy used the standard blackbody source as the actual object for temperatures of 1090.5 °C, 1197.8 °C, 1295.4 °C and 1404.0 °C. The object temperatures were calculated using multi-wavelength pyrometry using the spectral response curves in Figs. 3–5. The calculations assume unknown emissivities in the multi-wavelength method and the model assumptions listed in Section 2.

The temperature errors using the original spectral response curves obtained at different calibration temperatures without the stray light corrections are shown in Fig. 6. When the calibration temperature greatly differs from the temperature of the measured object so that the spectral intensity distributions are significantly different, the temperature solution error will be larger. For example, for the measurement source at 1197.8 °C, the temperature error calculated using the spectral response curve obtained at a calibration source with the same temperature, is only 1.1 °C. Using the spectral response curve at a calibration temperature of 1404.0 °C increased the temperature error to 27.1 °C.

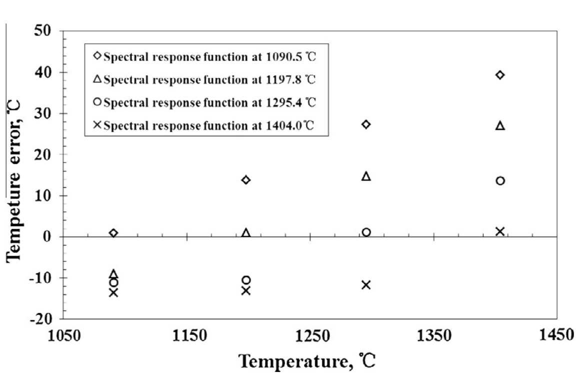

Fig. 6. Temperature errors using the original spectral response curves obtained at different calibration temperatures without stray light corrections.

However, the corrected spectral response curves with the stray light corrections results in much better temperature as shown in Fig. 7 with smaller temperature errors even for different response curves and different measurement temperatures. For example, using the spectral response curve for a calibration temperature of 1404.0 °C, the temperature error when measuring the source at 1197.8 °C is 2.0 °C which is very accurate. When the average corrected spectral response curve is used, the temperature errors for the investigated temperatures (1090.5 °C, 1197.8 °C, 1295.4 °C, 1404.0 °C) are all within 2.7–3.0 °C. The results illustrate that the stray light corrections in the multi-wavelength pyrometry algorithm can guarantee excellent results for this near-infrared multi-wavelength pyrometer.

5. Conclusions

Spectral stray light is a major concern for applications of spectrometers in colorimetry, photometry and optical spectroscopy. Multi-wavelength pyrometry uses the spectral radiation intensity measurements at multiple wavelengths to improve the response. The purpose of this study is to investigate the spectral stray light effects on radiation temperature measurements for a near-infrared multi-wavelength pyrometer. Spectral stray light corrections were measured for the pyrometer using a pulsed tunable laser source for wavelengths of 0.41–2.63 μm. The existence of spectral stray light in the near-infrared spectral region was experimentally verified. A matrix correction method was used for the spectral stray light in the multi-wavelength pyrometer to improve the temperature measurement accuracy. The spectral response characteristics of the multi-wavelength pyrometer were calibrated using a standard high-temperature blackbody source with and without consideration the effects of the spectral stray light. With the spectral stray light correction, the corrected spectral response gave more accurate measurements of the spectral radiation intensity even when the spectral distribution of the object differed significantly from that of the blackbody calibration source. The spectral stray light corrections significantly improve the accuracy of the multi-wavelength pyrometer at one blackbody source calibration temperature which provides a clear, simplified calibration procedure, unlike the temperature calibration methods for general optical pyrometers. The temperature measurement accuracy of the spectral stray light compensated multi-wavelength pyrometer was further verified through high-temperature measurement tests.

Conflict of interest

The authors declare that they have no conflict of interest.

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