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Inverse analysis of non-uniform temperature distributions using multispectral pyrometry

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HIGHLIGHTS

- Multispectral pyrometry was developed to deduce temperature area distribution.
- Transform a spot pyrometer into a pyrometer with enhanced spatial resolution.
- Temperature area fraction function is defined to represent temperature distribution.
- Inverse analysis of non-uniform temperature distribution verify this method.
- Provide reference for use of spot pyrometer for sub-pixel temperature measurement.

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ABSTRACT

Optical diagnostics can be used to obtain sub-pixel temperature information in remote sensing. A multispectral pyrometry method was developed using multiple spectral radiation intensities to deduce the temperature area distribution in the measurement region. The method transforms a spot multispectral pyrometer with a fixed field of view into a pyrometer with enhanced spatial resolution that can give sub-pixel temperature information from a "one pixel" measurement region. A temperature area fraction function was defined to represent the spatial temperature distribution in the measurement region. The method is illustrated by simulations of a multispectral pyrometer with a spectral range of 8.0–13.0 μm measuring a non-isothermal region with a temperature range of 500–800 K in the spot pyrometer field of view. The inverse algorithm for the sub-pixel temperature distribution (temperature area fractions) in the "one pixel" verifies this multispectral pyrometry method. The results show that an improved Levenberg–Marquardt algorithm is effective for this ill-posed inverse problem with relative errors in the temperature area fractions of (−3%, 3%) for most of the temperatures. The analysis provides a valuable reference for the use of spot multispectral pyrometers for sub-pixel temperature distributions in remote sensing measurements.

1. Introduction

Advanced optical pyrometers based on one-color pyrometry, two-color pyrometry or multispectral pyrometry can make non-contact temperature measurements of combustion flames or hot surfaces in industrial applications and scientific research. One/two/three-color imaging pyrometers with image sensors are widely used for two-dimensional temperature distribution measurements [1–14]. However, these limited spectrum channel (one-color, two-color or three-color) image pyrometers are restricted by the complex instrumentation.

As an improvement over one-color or two-color pyrometry, multispectral pyrometry is more promising for accurately determining temperatures from spectral intensity measurements using multiple spectra [15–26]. Multispectral measurements have been used to overcome the difficulties of temperature inverse solutions arising from the unknown spectral emissivity. More spectral measurement data significantly reduces the uncertainty due to the unknown spectral emissivity. Theoretical analyses and experimental techniques for multispectral pyrometry have been widely studied in various applications. For example, Ng and Fralick [17] performed extensive research on developing a multispectral

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pyrometer for temperature measurements of thermal barrier coatings, glass materials, and combustor gases at elevated temperatures for aerospace applications. Madura et al. [19] used multispectral IR pyrometry for remote temperature measurements of seawater with sun radiation disturbances. This pyrometer provided high resolution, accurate temperature measurements of the seawater surface. Estevadeordal et al. [22] used high-speed multicolor pyrometry to measure radiation temperatures of hot particulate bursts generated from a combustor for various engine conditions. The experimental results illustrated the characteristics of the hot particulate bursts. Methods were developed to identify and filter the burst signals based on the processed data. Fu et al. [23–26] recently developed a series of multispectral pyrometers with visible and near-infrared spectral ranges for temperature measurements of various objects (combustion flames, non-transparent surfaces, and semi-transparent materials) and various harsh environments. However, most multispectral pyrometers operate in a working mode which acquires that the spectral radiation signal is emitted from a small region. The calculated temperature based on the signal represents the average temperature of a small region defined as a spot because the measurement region is assumed to be isothermal.

Spatial resolution is an important parameter for optical pyrometers especially for remote temperature measurements of non-isothermal objects. Although a general multispectral pyrometer has superior hyperspectral resolution, it has limited spatial resolution which is only applicable for spot measurements in a specified field of view. The measurement region in the field of view of a multispectral pyrometer corresponds to one pixel of the sensor. The measurement region area detected by a pyrometer increases with increasing measurement distance for a fixed field of view. A smaller field of view improves the optical pyrometer spatial discrimination. However, pyrometers are unable to discriminate sub-pixel temperature information in the "one pixel" corresponding to the small measurement region.

There is a significant need for a high spatial discrimination capability in optical pyrometers operating with a fixed field of view for remote sensing measurements. The output of the measurement signal from a non-isothermal region received by a spot optical pyrometer reflects the weighted temperature of this non-isothermal region. This weighted temperature is then not able to represent the actual temperature information in the non-isothermal region. Therefore, Methods are needed to characterize the sub-pixel temperature information from a spot optical pyrometer. The purpose of this paper is to develop multispectral pyrometry method using multiple spectral intensity data points to determine the sub-pixel temperature distribution in the non-isothermal region. A general spot multispectral pyrometer operating with a wide field of view can then be transformed into a pyrometer with superior spatial resolution. The multispectral pyrometry analysis for the sub-pixel temperature distribution is introduced first. Then, a simulated case shows how inverse solutions of the temperature distribution are determined using various optimization algorithms to verify this measurement method. The analysis provides a valuable reference for applications of spot multispectral pyrometers for remote sensing measurements.

2. Method

The sketch of how a spot multispectral pyrometer is used for remote measurements is shown in Fig. 1. The radiation flux emitted from the measurement region (defined as a spot) is converted to the output multispectral radiation intensities by the pyrometer. The measurement region in the field of view corresponds to one pixel of the pyrometer sensor. Therefore, the temperature distribution in the measurement region may be looked on as the sub-pixel temperature information in the "one pixel". The temperature can be determined from the output signals of the multispectral radiation intensities using traditional multispectral pyrometry. The calculated "one pixel" temperature only represents the weighted temperature of the non-isothermal measurement region and is unable to characterize the temperature distribution information (as shown in the pseudo color image in Fig. 1) in the measurement region in the field of view of the optical instrument.

This multispectral pyrometry method operated at a new mode was used to determine the sub-pixel temperature distribution differs from traditional multispectral pyrometry. The processing procedure is introduced here.

The temperature range in the non-isothermal measurement region was divided into N discrete temperature sub-ranges, $(T_1 - \Delta T/2, T_1 + \Delta T/2), \ldots, (T_i - \Delta T/2, T_i + \Delta T/2), \ldots, (T_N - \Delta T/2, T_N + \Delta T/2)$, each with the same interval $\Delta T = T_i - T_{i-1}$. $S(T_i)$ is defined as the area with a temperature range of $(T_i - \Delta T/2, T_i + \Delta T/2)$ in the measurement region to describe the temperature distribution characteristics of the non-isothermal measurement region. Then, the total area of the region, S_{sum}, can be expressed as:

$$S_{sum} = \sum_{i=1}^{N} S(T_i) \tag{1}$$

The temperature area fraction, s_i, which is the ratio of the area with a temperature range of $(T_i - \Delta T/2, T_i + \Delta T/2)$ to the total area of the measurement region can be expressed as follow:

$$s_i = S(T_i)/S_{sum}, \quad i = 1, 2, \ldots, N \tag{2}$$

where $\sum_{i=1}^{N} s_i = 1$.

The total spectral radiation intensity, I_λ, emitted from the non-isothermal measurement region measured by the spot pyrometer is

$$I_\lambda = \sum_{i=1}^{N} I_{\lambda,i} = \sum_{i=1}^{N} \varepsilon I_{b\lambda}(T_i) S(T_i)/S_{sum} = \sum_{i=1}^{N} \varepsilon I_{b\lambda}(T_i) s_i \tag{3}$$

where λ is the wavelength, $I_{b\lambda}(T_i)$ is the spectral radiation intensity distribution of a blackbody at temperature T_i, ε is the emissivity which is known and assumed to be constant for a gray measurement region, and $I_{\lambda,i}$ is the spectral radiation intensity emitted from the area with a temperature range of $(T_i - \Delta T/2, T_i + \Delta T/2)$ in the measurement region. Eq. (3) describes the relationship between the total spectral radiation intensity, I_λ, and s_i in the measurement region in the field of view of the optical pyrometer.

The temperature area fraction, s_i, can be used to form the average temperature, T_a, of the measurement region as:

$$T_a = \sum_{i=1}^{N} T_i s(T_i) \tag{4}$$

Eqs. (3) and (4) show that the temperature area fraction, s_i, reflects the temperature and radiation intensity distribution information together with ΔT and N in the measurement region.

If the non-isothermal measurement region is assumed to be isothermal, the measured spectral radiation intensity can be expressed in the general format used for traditional multispectral pyrometry:

$$I_\lambda = \varepsilon_{iso} I_{b\lambda}(T_{iso}) \tag{5}$$

where T_{iso} is the temperature and ε_{iso} is the emissivity at the isothermal condition. The solutions of $(T_{iso}, \varepsilon_{iso})$ can be determined through multiple measurements at M wavelengths of $(\lambda_1, \ldots, \lambda_j, \ldots, \lambda_M)$ using the least squares algorithm by minimizing