Infrared Physics & Technology 66 (2014) 49–55

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Temperature measurements of high-temperature semi-transparent infrared material using multi-wavelength pyrometry

Tairan Fu [a,b,*], Jiangfan Liu [a], Jiaqi Tang [a], Minghao Duan [a], Huan Zhao [a], Congling Shi [c]

[a] Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, PR China

[b] Beijing Key Laboratory of CO_2 Utilization and Reduction Technology, Beijing 100084, PR China

[c] China Academy of Safety Science & Technology, Beijing 100029, PR China

HIGHLIGHTS

- Temperature measurement method of semi-transparent infrared material is developed.
- Multi-wavelength pyrometry is used to determine interior temperature distribution.
- Apparent spectral radiation properties of investigated ZnS material are analyzed.
- Spectrum optimization of optical pyrometry for ZnS material are investigated.
- Inversion temperature accuracy using optical pyrometry is good for applications.

ARTICLE INFO

Article history:
Received 12 May 2014
Available online 2 June 2014

Keywords:
Temperature
Semi-transparent
Multi-wavelength
Pyrometry
Optical properties

ABSTRACT

Temperature measurements inside semi-transparent materials are important in many fields. This study investigates the measurements of interior temperature distributions in a one-dimensional semi-transparent material using multi-wavelength pyrometry based on the Levenberg–Marquardt method (LMM). The investigated material is semi-transparent Zinc Sulfide (ZnS), an infrared-transmitting optical material operating at long wavelengths. The radiation properties of the one-dimensional semi-transparent ZnS plate, including the effective spectral–directional radiation intensity and the proportion of emitted radiation, are numerically discussed at different wavelengths (8.0–14.0 μm) and temperature distributions (400–800 K) to provide the basic data for the temperature inversion problem. Multi-wavelength pyrometry was combined with the Levenberg–Marquardt method to resolve the temperature distribution along the radiative transfer direction based on the line-of-sight spectral radiation intensities at multiple wavelengths in the optimized spectral range of (11.0–14.0 μm) for the semi-transparent ZnS plate. The analyses of the non-linear inverse problem show that with less than 5.0% noise, the inversion temperature results using the Levenberg–Marquardt method are satisfactory for linear or Gaussian temperature distributions in actual applications. The analysis provides valuable guidelines for applications using multi-wavelength pyrometry for temperature measurements of semi-transparent materials.

1. Introduction

Optical radiation pyrometry is widely used for measuring combustion flame temperatures or surface temperatures in industrial applications and scientific research [1–28]. Mori et al. [13] presented an experimental study of the convective heat transfer and flow field characteristics in a rotating rotor cascade and the surface temperature distribution on a rotating heated blade measured by means of infrared thermography. Lu et al. [17] described a three-color pyrometry algorithm based on a color CCD camera with the measured particle–surface temperatures and flame temperatures agreeing well with thermocouple measurements. Densmore et al. [24] used a high-speed image pyrometer based on the two-color ratio method for temperature measurements of explosive and combustion processes. Guo et al. [26] used a digital camera to measure full-field soot temperatures and soot volume fractions in axisymmetric flames. Kappagantula et al. [27] measured the spatial temperature distribution of combustion products by coupling point source temperature measurements from a multi-wavelength

* Corresponding author at: Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing 100084, PR China. Tel.: +86 10 62786006.

E-mail address: trfu@mail.tsinghua.edu.cn (T. Fu).

http://dx.doi.org/10.1016/j.infrared.2014.05.016
1350-4495/

pyrometer with irradiance measurements from an infrared camera to produce a highly discretized thermal map. Estevadeordal et al. [28] used a high-speed multicolor pyrometry to measure radiation temperatures of hot particulate bursts generated from a combustor.

In most applications using optical radiation pyrometers, for opaque materials (for example, metals and alloys), the measured radiation comes from the surface and the temperature determined from the measured effective emitted radiation is only the "surface" temperature. However, for semi-transparent materials (for example, glass, coatings and polymers), the measured radiation received by the radiation pyrometer comes not only from the surface radiation and reflected background radiation, but also from the radiation emitted inside the material and transmitted background radiation passing through the material along the radiation transfer direction. The temperature determined using traditional pyrometry then does not correspond to the surface temperature. The measured temperature can then be looked upon as the coupled "apparent temperature" related to the temperature distribution inside the material, the transmitted environmental temperature and the reflected environmental temperature. Deducing the "true" temperature distribution from the coupled effective radiation is a major obstacle in applications using radiation pyrometers for semi-transparent materials. Some research has focused on this subject. Pfefferkorn et al. [29] used a long-wavelength pyrometer to measure the surface temperatures of a dense zirconia ceramic that was semitransparent at shorter wavelengths. The process avoided the effects of the semi-transparent radiation properties of zirconia ceramic. Hajji and Spruiell [30] investigated the use of radiation pyrometry for semi-transparent materials and derived a temperature expression for nonisothermal semi-transparent gray polymer materials. Daniel and Gustave [31] used a near-infrared multi-wavelength pyrometer to simultaneously calculate the surface and bulk temperatures of semi-transparent materials (zirconia barrier coating and glass) based on a simplified radiative transfer model. Nagtegaal et al. [32] presented a numerical analysis of the multi-wavelength optical method to determine temperature profiles in hot glass based on Tikhonov regularization and the L-curve algorithm.

However, current research works are mostly related to semi-transparent zirconia ceramic and glass. There are few studies of noncontact temperature measurements of semi-transparent Zinc Sulfide (ZnS) which is widely used as an infrared semi-transparent optical window material which has the advantages of high mechanical strength, high hardness, erosion resistant, low temperature coefficient of the refractive index, and excellent high-temperature optical properties [33]. This study investigates ZnS as a representative semi-transparent material. The noncontact measurements of the temperature information in the semi-transparent ZnS material are necessary for the structure-stress analysis, optical property examinations and other applications of ZnS at different thermal conditions. Due to the excellent optical transmission from the visible to infrared wavelengths of ZnS material, the measured effective radiation intensity information received by the optical pyrometer is strongly affected by the reflected and transmitted background radiation. The proportion of the emitted radiation relating to the semi-transparent ZnS material temperature will be small in the visible to infrared wavelengths. Thus, the "true" temperature distributions are difficult to accurately derive from effective radiation intensity data recorded by a radiation pyrometer. This study investigates radiation temperature measurements of a semi-transparent ZnS plate using infrared multi-wavelength pyrometry to determine the temperature distribution along the radiative transfer direction based on the line-of-sight radiation intensities at multiple wavelengths. The issues, including the apparent spectral radiation properties, measurement spectrum optimization, and inversion temperature accuracy, will be investigated. The analysis provides a valuable reference for the applications of multi-wavelength pyrometry for temperature distribution measurements in semi-transparent materials.

2. Radiation properties of a one-dimensional ZnS plate

The radiative transfer process in a one-dimensional semi-transparent absorbing–emitting plate with ideal optical smooth interfaces is shown in Fig. 1. The equation describing the spectral radiation intensity distribution along the radiative ray direction neglecting scattering is [34]:

$$\frac{dI_\lambda}{ds} = \alpha_\lambda(s)I_{b\lambda}(s) - \alpha_\lambda(s)I_\lambda(s) \tag{1}$$

where I_λ is the spectral radiation intensity distribution at wavelength λ, $I_{b\lambda}$ is the blackbody spectral radiation intensity distribution at the same temperature, α_λ is the spectral absorption coefficient and s is the position vector along the radiative transfer direction. Define θ to be the angle between the x coordinate axis and the ray direction. The spectral radiation intensity is expressed as I_λ^+ when $0 \leqslant \theta \leqslant 90°$, while the spectral radiation intensity is expressed as I_λ^- when $90 < \theta \leqslant 180°$. Eq. (1) can be rewritten as:

$$\begin{cases} I_\lambda^+(\tau_{d\lambda},\mu) = I_\lambda^+(0,\mu)e^{-\tau_{d\lambda}/\mu} + \int_0^{\tau_{d\lambda}} I_{b\lambda}(\tau_\lambda^*)e^{-(\tau_{b\lambda}-\tau_\lambda^*)/\mu}d\tau_\lambda^*/\mu \\ I_\lambda^-(0,\mu) = I_\lambda^-(\tau_{d\lambda},\mu)e^{\tau_{d\lambda}/\mu} - \int_0^{\tau_{d\lambda}} I_{b\lambda}(\tau_\lambda^*)e^{\tau_\lambda^*/\mu}d\tau_\lambda^*/\mu \end{cases} \tag{2}$$

where the optical thickness $\tau_\lambda(x) = \int_0^x \alpha_\lambda(x^*)dx$, $\mu = \cos\theta_r$ and $v = \cos\theta_i$. The boundary conditions for the radiative transfer are:

$$\begin{cases} \tau_\lambda = 0, \; I_\lambda^+(0,\mu) = n^2(1-\rho)I_e^+ + \rho I_\lambda^-(0,\mu) \\ \tau_\lambda = \tau_{d\lambda}, \; I_\lambda^-(\tau_{b\lambda},\mu) = n^2(1-\rho)I_e^- + \rho I_\lambda^+(\tau_{b\lambda},\mu) \end{cases} \tag{3}$$

where I_e^+ and I_e^- are the background radiation intensities, n is the real part of the complex refractive index, and ρ is the single-surface reflectance of the interface for unpolarized radiation which is given by the Fresnel equation [33,34]:

$$\rho = \frac{\rho_s}{2}\left(\frac{(A-\sin\theta_i\tan\theta_i)^2+B^2}{(A+\sin\theta_i\tan\theta_i)^2+B^2}+1\right) \tag{4}$$

where A and B are functions of the complex refractive index (k is the imaginary part) given by:

$$\begin{cases} 2A^2 = \left[\left(n^2-k^2-\sin^2\theta_i\right)^2 + 4n^2k^2\right]^{1/2} + \left(n^2-k^2-\sin^2\theta_i\right) \\ 2B^2 = \left[\left(n^2-k^2-\sin^2\theta_i\right)^2 + 4n^2k^2\right]^{1/2} - \left(n^2-k^2-\sin^2\theta_i\right) \end{cases} \tag{5}$$

The measured effective radiation from a semi-transparent plate received by a pyrometer includes the emitted surface radiation, the radiation emitted from inside the plate, the reflected background

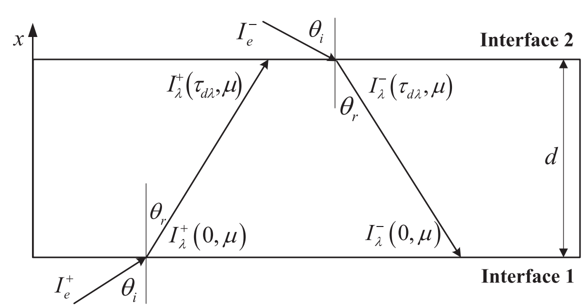

Fig. 1. Radiative transfer inside a one-dimensional absorbing–emitting plate.