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Experimental study of the relationships between the spectral emissivity of brass and the temperature in the oxidizing environment

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HIGHLIGHTS

- Spectral emissivity of brass is reported.
- The resonance of spectral emissivity is observed.
- Contribution to the emissivity by oxidation is mainly from the first 4 h.
- Behavior of emissivity versus temperature at the given heating time is discussed.
- Behavior of emissivity versus heating time at the given temperature is studied.

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ABSTRACT

Effect of surface oxidization on the spectral emissivity of brass is studied over the temperature range from 800 to 1070 K at the wavelength of 1.5 μm. The temperature of brass surface is measured by averaging the two R-type platinum–rhodium thermocouples. The radiant energy emitted by the brass surface is received by an InGaAs photodiode detector. Two kinds of relationships between the spectral emissivity and the temperature are investigated in the oxidizing environment at the elevated temperature. One is the variation of spectral emissivity with the heating-duration time at the given temperature. The other is the variation of spectral emissivity with the temperature at the given heating-duration time. The interference effect of radiation coming from the brass surface and coming from the oxidization film is discussed when the oxidation film on the surface is grown. The resonant structures of spectral emissivity are observed during the whole heating period, in particular at the early stage of heating duration. The analytic formula of spectral emissivity versus the temperature is derived at the heating-duration time of 30, 60, 90, 120, 150, 180, 210, 240, 270 and 300 min, respectively. The conclusion is obtained that coefficients of analytic expressions between the spectral emissivity and the temperature are different from each other for the experimental results obtained at the different heating-duration time, though the polynomial functional form is suitable to fit all the measurements obtained in the present work.

1. Introduction

It is well-known that precise determination of temperature has a strong bearing on both the process control and the final product quality of various kinds of metal materials, such as ion, steel, aluminum, and copper. However, these metal materials are always moving in most processes of manufacture. As a result, we determine their temperature only by the non-contact radiation measurement method. For this reason, in recent several decades, numerous radiation thermometers have been invented and put into practical use.

Radiation thermometer can be divided into single-wavelength thermometry and multi-wavelength thermometry. Single-wavelength thermometry can give the definite temperature of a target, provided that the accurate relationship between the spectral emissivity and the temperature can be obtained. However, such relationship is difficult to be determined exactly [1]. The main reason is that the metal materials noted above are exposed in air at an elevated temperature for a long time in the process of production, and surface oxidation is traveling through the whole period of manufacture. As we know, the spectral emissivity can easily change due to physical and chemical conditions of surface

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[2–6], in particular to surface oxidation. Any changes of surface conditions can make the spectral emissivity reported in the literature become less valuable or sometimes even no value. Therefore, even if the spectral emissivity of these materials could be available in the literature, there are still problems with this parameter during the measurement with the single-wavelength thermometry. More importantly, it is impossible to find out the measurements of spectral emissivity at any given temperatures. That is, the spectral emissivity at some temperatures is only obtained by inferring according to a given analytic model, in which the variation of spectral emissivity with temperature is assumed. In a sense, how to choose the analytic model is a key problem to increase the temperature measurement accuracy for the single-wavelength thermometry. Similarly, to extrapolate the accurate temperature of a target, a prior knowledge between the spectral emissivity and the wavelength and temperature at various surface conditions is also very important [7–9] for the multi-wavelength thermometry.

Numerous relationships between the spectral emissivity and the wavelength and temperature can be available for various materials. However, as seen in the literature, most of these analytic models are obtained in the vacuum condition, which do not include the effect of surface oxidation on the spectral emissivity. As we know, it is impossible to produce the metal materials noted above in such an ideal condition in industry. Obvious errors must be introduced into the temperature measurements if these analytical models are put into practical use in the oxidizing environment, in particular at an elevated temperature. In this work, we can also clearly see that the surface oxidation can influence the analytic relationships between the spectral emissivity and the temperature. For this reason, some work should be done so as to clarify the effect of surface oxidation on the spectral emissivity, and to determine the accurate analytic models in the oxidizing environment, prior to the practical applications of radiation thermometry.

We select the brass specimen as the target at this work. The main reasons are twofold. One is that the surface temperature of brass in production is measured only by radiation thermometer due to the movement in the process of manufacture. One is that the effect of surface oxidation on the spectral emissivity of brass has been known very little, in particular at an elevated temperature in air. Very few analytic models between the spectral emissivity and the temperature are studied in detail in the past several decades. Therefore, to measure the surface temperature of brass in production as accurately as possible, we must clarify the effect of surface oxidization on the spectral emissivity.

The aim of the present work is to obtain the analytic relationships between the spectral emissivity of brass and the temperature at the given wavelength when the surface oxidation is taken into account. Two kinds of relationships between the spectral emissivity and the temperature are investigated in the oxidizing environment at the elevated temperature. One is that the spectral emissivity varies with the heating-duration time at the given temperature. The other is that the spectral emissivity varies with the temperature at the given heating-duration time.

This paper is organized as follows. The principle and structure of the experimental setup is briefly outlined in the next section. In Section 3, the spectral emissivity of brass specimen is measured, and the corresponding experimental results are reported. The complex resonant peaks of spectral emissivity are observed when the oxidation film on the surface of specimen is grown. The variation of spectral emissivity with the heating-duration time is studied, in particular at the early stage of heating duration. The analytic expressions between the spectral emissivity and the temperature are accurately fitted by using the same polynomial functional form. Concluding remarks are given in Section 4.

2. Measurement principle and experimental setup

2.1. Measurement principle

Here we only briefly introduce the measurement principle of the present experimental setup. The monochromatic radiant energy emitted from a real surface is forever smaller than that from a perfect blackbody at the same temperature. The spectral emissivity is the ratio of the monochromatic radiant energy emitted by a real surface at temperature T to that emitted by a perfect blackbody at the same temperature ($T = T_b = T_s$). According to this, the spectral emissivity ε_λ can be expressed as

$$\varepsilon_\lambda = \frac{L_{\lambda,T_S}}{L_{\lambda,T_b}}, \tag{1}$$

where ε_λ can be calculated, provided that the monochromatic radiant energy L_{λ,T_S} and L_{λ,T_b} at the same temperature T and wavelength λ emitted, respectively, by a real surface and a perfect blackbody are measured. The monochromatic radiant energy emitted by a perfect blackbody at the given λ and T_b is expressed by the Planck law

$$L_{\lambda,T_b} = 2\pi hc^2\lambda^{-5}\left[\exp\left(\frac{hc}{\lambda kT_b}\right) - 1\right]^{-1}, \tag{2}$$

where h is the Planck's radiation constant; c is the speed of light; k is the Boltzmann constant; and T_b is the temperature of a perfect blackbody.

In the experimental setup, the radiant energy P_1 coming from a perfect blackbody can be written as

$$P_1 = \frac{\pi^2}{4}\left(\frac{D}{f'}\right)^2 \tau_\circ A \int_{\lambda_1}^{\lambda_2} \tau_\lambda L_{\lambda,T_b}\, d\lambda, \tag{3}$$

where D and f' are the aperture diameter and focal length of the optical receiving system, respectively. τ_0 is the propagation coefficient of the atmosphere, A is the area of sensitive unit of the detector, λ_1 and λ_2 are the spectral limits of the optical receiving system used to select the spectral band, τ_λ is the total transmissivity of optical receiving system. To measure the normal spectral emissivity as accurately as possible, the detector should be perpendicular to the surface of specimen as accurately as possible.

In combination with Eqs. (2) and (3), the radiant energy P_1 of a perfect blackbody can be expressed as

$$P_1 = \frac{\pi^2}{4}\left(\frac{D}{f'}\right)^2 \tau_\circ A \int_{\lambda_1}^{\lambda_2} \tau_\lambda 2\pi hc^2\lambda^{-5}\left[\exp\left(\frac{hc}{\lambda kT_b}\right) - 1\right]^{-1} d\lambda. \tag{4}$$

The bandwidth $\Delta\lambda$ (only about 20 nm) of the interference filter used in the setup is very narrow. Within such a narrow bandwidth, we can approximately regard τ_λ as a constant, although τ_λ is never constant between λ_1 and λ_2 for a real infrared thermometer. And then, Eq. (4) can be rewritten as

$$P_1 = C \cdot \left[\exp\left(\frac{hc}{\lambda kT_b}\right) - 1\right]^{-1}, \tag{5}$$

where

$$C = \frac{\pi^3}{2}\left(\frac{D}{f'}\right)^2 \tau_\circ A\tau_\lambda hc^2\lambda^{-5}\Delta\lambda. \tag{6}$$

The radiant energy P_2 coming from a real surface can be expressed as

$$P_2 = \frac{\pi^2}{4}\left(\frac{D}{f'}\right)^2 \tau_\circ A \int_{\lambda_1}^{\lambda_2} \varepsilon_\lambda \tau_\lambda L_{\lambda,T_s}\, d\lambda. \tag{7}$$

Within a very narrow bandwidth, similarly, P_2 can be simplified as