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# Spectral emissivity model of steel 309S during the growth of oxide layer at 800–1100 K

Wenjie Zhu, Deheng Shi *, Zunlue Zhu, Jinfeng Sun

*College of Physics and Material Science, Henan Normal University, Xinxiang 453007, China*

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ABSTRACT

This work strived to determine the analytical relationships between the spectral emissivity and the wavelength at different temperatures during the growth of oxide layer on the specimen surface of steel 309S. In the experiment, the spectral emissivity was measured at eight wavelengths, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, and 2.1 μm, at temperatures from 800 to 1100 K in increments of 20 K by multispectral radiation thermometry. To accurately measure the normal spectral emissivity, the detector employed in the thermometry should be perpendicular to the surface of specimens as accurately as possible. The temperature of specimen surface was measured by the two thermocouples, which were symmetrically welded onto the front surface of specimens. The average of their readings was regarded as the true temperature. With the spectral emissivity measured here, the variation in the spectral emissivity with wavelength was evaluated at different temperatures and different heating times. Ten emissivity models were evaluated. The effect of number of the parameters used in the models on the fitting accuracy was studied. Both the five-parameter LLWE and LWE models were very suitable for fitting the spectral emissivity and could farthest relieve the effect of heating time on the accuracy of temperature prediction. The uncertainties in the temperature prediction of steel 309S specimens were basically within 10 K by thermometry using the two models over the present temperature and wavelength ranges.



## 1. Introduction

Radiation thermometry is an indirect technique for measuring a body temperature using radiation emitted from its surface. This technique is very effective for a fast-moving body such as various steels in manufacturing processes. Unfortunately, this technique requires some prior knowledge of spectral emissivity of a body if we want to use it to measure the true temperature accurately [1]. As we know, spectral emissivity may observably vary with wavelength and temperature. More importantly, even if the wavelength and temperature are fixed, emissivity can easily change due to different physical and chemical surface conditions, especially to the surface oxidization of various metals exposed in air at an elevated temperature (i.e., above 800 K for steels in various production processes) for a long time [2]. It is very hard to obtain the accurate spectral emissivity data, which can be directly used in radiation thermometry to accurately evaluate the true temperature in various circumstances [3,4]. That is, to accurately measure the temperature of various steels in production processes by thermometry, we must understand the effect of surface oxidization on the spectral emissivity of steels.

To accurately understand the effect of surface oxidization on the spectral emissivity of various steels, an amount of experimental work [2,4–14] was done in recent years at selected wavelengths and selected temperatures. For example, Kobayashi et al. [2] in 1999 used the radiation thermometry to measure the time variation of normal spectral emissivity of several steels at wavelengths ranging from 0.55 to 5.3 μm over a temperature range from 1053 to 1473 K. Pujana et al. [5] in 2007 employed their precision radiometer to evaluate the spectral emissivity of steels as a function of surface oxidization at wavelengths of 2.12, 4 and 8 μm and at 959 and 1073 K. Cao et al. [6] in 2012 used Fourier Transform Infrared (FTIR) spectrometer to measure the time variation in the spectral emissivity of several steels with wavelength at different oxidization states over an extensive wavelength range at several selected temperatures. Švantner et al. [7] in 2013 measured the spectral emissivity of AISI 1015 steel at 523 K over a wide wavelength range. However, they did not investigate the effect of surface oxidization on the spectral emissivity. Very recently, our group [4,8–11] measured the normal spectral emissivity of several steels at 1.5 μm over a temperature range from 800 to 1100 K. Our group also evaluated the time variation in the normal spectral

* Corresponding author.
*E-mail address:* scattering@sina.com.cn (D. Shi).

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emissivity with surface oxidization during the 6 h heating time at a certain temperature and determined the analytic relationships between the normal spectral emissivity and the heating time. From the experimental work [2,4–6,8–11], we can clearly see that the surface oxidization has great effect on the spectral emissivity. However, all these studies [2,4–6,8–11] did not evaluate any steel emissivity models varying with wavelength and temperature, let alone the effect of surface oxidization on the fitting accuracy of these emissivity models during the growth of oxide layer.

Wen [12] in 2010 used Fast Infrared Array Spectrometer (FIAS) to measure the spectral emissivity of six steels at 700, 800 and 900 K over a wavelength range from 1.2 to 4.8 μm. With these emissivity data, on one hand, Wen [12] investigated the analytical models between the spectral emissivity and the wavelength, temperature and then applied these models to the thermometry so as to infer the steel temperature; on the other hand, Wen studied the effect of heating time on the spectral emissivity, but he did not evaluate the effect of surface oxidization on the fitting accuracy of emissivity models. Wen and Lu [13] in 2010 used the FIAS to measure the spectral emissivity of three types of steels at 700, 800 and 900 K over a wavelength range from 1.2 to 4.8 μm. They [13] used six emissivity models to fit the variation in the emissivity with wavelength and temperature and then applied these models to the thermometry so as to infer the surface temperature of corresponding steels. Wen [14] in 2011 used the FIAS to measure the spectral emissivity of several steels at 700, 800 and 900 K at wavelengths ranging from 1.2 to 4.8 μm. As with their previous work [12,13], Wen [14] first used several types of emissivity models to fit the experimental data and then applied these models to the thermometry to validate their accuracy in the temperature prediction. All these investigations [12–14] examined the analytic relationships between the spectral emissivity and the wavelength, temperature.

Summarizing the results noted above, we find that no experiments reported the effect of surface oxidization on the fitting accuracy of emissivity models till today, though some work in detail studied the effect of heating time on the spectral emissivity [2,4–6,8–12]. In our recent work [4,8–11], we found that the uncertainties in the temperature and normal spectral emissivity of various steels brought about only by the surface oxidization could exceed 10 K and 10%, respectively. Can such surface oxidization of steels generate any observable effect on the accuracy of temperature prediction in thermometry? How can we farthest relieve the effect of surface oxidization on the accuracy of the temperature prediction? To accurately predict the surface temperature of steels by thermometry, we must thoroughly understand the effect of surface oxidization on the fitting accuracy of emissivity models used.

We select steel 309S as the target of this paper. The reason is that no emissivity models of this steel can be available, let alone the effect of surface oxidization on the fitting accuracy of emissivity models. In the next section, we will briefly describe the experimental principle. In Section 3, we will in brief introduce the experimental setup used. In Section 4, we describe the measurement procedure. In Section 5, we report the spectral emissivity over a wavelength range from 1.4 to 2.1 μm at several selected temperatures and evaluate some emissivity models at different heating time for the accuracy of temperature predictions. In Section 6, we give some concluding remarks. It should be noticed that we employ the nomenclature "heating time" to represent the "surface oxidization" in the following descriptions.

## 2. Experimental principle

The thermometry employed in the experiment had eight wavelengths, which were 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0 and 2.1 μm, respectively. The bandwidth of each wavelength is approximately 20 nm. The eight wavelengths were obtained by the eight narrow-band interference filters mounted onto the chopper wheel. Each wavelength in thermometry can be regarded as a single-wavelength setup outlined in our earlier papers [4,8–11] when we measured the infrared radiances stemming from the specimen surface. Fig. 1 depicts the schematic diagram of positioning method of two thermocouples, one detector used in thermometry and one piece of specimens. In the experiment, the detector should be perpendicular to the specimen surface as accurately as possible so that we could measure the normal radiances as accurately as possible.

The specimen was heated to a certain temperature by an eddy current heater. The temperature of specimen surface was measured by the two thermocouples, which were symmetrically welded onto the front surface of specimens near the measuring area. The average of their readings was regarded as the true temperature of specimen surface.

Assuming that the $i$th wavelength of thermometry is $\lambda_i$ ($i$ = 1, 2, 3, 4, 5, 6, 7 and 8, respectively, corresponding to 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0 and 2.1 μm) and that the normal radiance received by the detector at $\lambda_i$ and $T$ is $P_i$, $P_i$ can be written as [4,8–11]

$$P_i = \frac{\pi^2}{4}\left(\frac{D}{f'}\right)^2 A \int_{\lambda_{i1}}^{\lambda_{i2}} \tau_\lambda \varepsilon(\lambda, T) L_{\lambda,T} d\lambda \tag{1}$$

where $T$ is the temperature of the specimen surface; $D$ and $f'$ are the aperture diameter and the focal length, respectively, of the optical receiving system in the thermometry; $A$ is the area of the sensitive unit of the detector; $\lambda_{i1}$ and $\lambda_{i2}$ are the spectral limits of the optical receiving system used to select the spectral bandwidth of the $i$th wavelength; $\tau_\lambda$ is the total transmissivity of the atmosphere and optical receiving system; and $\varepsilon(\lambda,T)$ is the normal spectral emissivity of specimens at $\lambda$ and $T$. Using Planck law, we re-write Eq. (1) as

$$P_i = \frac{\pi^2}{4}\left(\frac{D}{f'}\right)^2 A \int_{\lambda_{i1}}^{\lambda_{i2}} \tau_\lambda \varepsilon(\lambda, T) 2\pi hc^2 \lambda^{-5}\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]^{-1} d\lambda \tag{2}$$

where $h$ is the Planck constant; $c$ is the speed of the light; and $k$ is the Boltzmann constant. The band width $\Delta\lambda$ of each interference filter is approximately 20 nm, which is very narrow. In such a narrow bandwidth, the variation in $\tau_\lambda$ and $\varepsilon(\lambda,T)$ with wavelength at a certain temperature can be neglected. Therefore, we can approximately regard $\tau_\lambda$ and $\varepsilon(\lambda,T)$ as a constant, although $\tau_\lambda$ and $\varepsilon(\lambda,T)$ are never a constant between $\lambda_{i1}$ and $\lambda_{i2}$. With these considerations, Eq. (2) can be simplified as

$$P_i = C_i \cdot \varepsilon(\lambda_i, T)\left[\exp\left(\frac{hc}{\lambda_i kT}\right) - 1\right]^{-1} \tag{3}$$

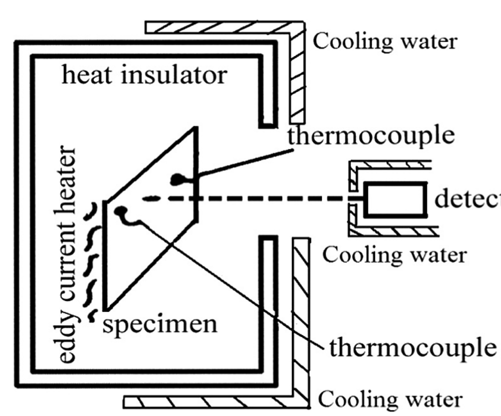


**Fig. 1.** Schematic diagram of positioning method of thermocouples, detector and specimen.