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The normal spectral emission characteristics of Ni-based alloys during oxidation at high temperatures

Shunan Zhao [a,b], Xunfeng Li [a,b,*], Xiulan Huai [a,b,*], Xiaoming Zhou [a], Keyong Cheng [a]

[a] Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China
[b] University of the Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

The emissivity change due to oxidation of the Ni-based alloys that are used for turbine blades in severe environment will cause large errors in radiation thermometry. In this paper, the normal spectral emissivity of three Ni-based alloys DZ125, DD6 and K465 is experimentally measured during oxidation at about 810, 914 and 998 °C in air. And the measurement wavelength varies from 1.35 to 2.35 μm. The combined standard uncertainties of the normal spectral emissivity are less than 3%. The oscillations of the emissivity are observed, and the effects of oxidation temperature, heating time and wavelength on the emissivity are investigated. The oscillations of the emissivity are produced with growth of the oxidation film by the interference effect between the direct transmission radiation and the transmission radiation after reflections by the substrate and air/film interface emitted by of the substrate. The oscillation extremums of the emissivity shift towards larger wavelengths as the oxidation process proceeds. The results show that the normal spectral emissivity increases basically with increasing temperature and decreasing wavelength except for the occurrence of the oscillations of the emissivity. The normal spectral emissivity increases rapidly at the initial heating time, and the change of emissivity becomes slow when the oxidation tends to be saturated gradually. Furthermore, the emissivity models versus heating time and wavelength are established, which fit the experimental results very well. The relative errors of the fitting models for emissivity are less than 4%.

1. Introduction

Turbine blades are used in the severe environment, such as high temperature and high pressure. Furthermore, rotor blades are under the high-speed revolution situation. The turbine inlet temperature (TIT) increases as high as possible, which is driven by the requirement for higher efficiency. Thus, the turbine blades are one of the most vulnerable parts in the aero-engine. It is necessary to measure the accurate temperature of the turbine blades real-timely during the working process to protect them from over-temperature exposure. However, the methods of contact temperature measurement are undesirable in measuring the blades temperature because of its short lifetime at that severe environment [1,2]. A more accurate, nondestructive and easy-using non-contact radiation thermometry is needed. Radiation thermometry can be divided into three categories according to their principles: spectral radiation thermometry (SRT), dual-wavelength radiation thermometry (DWRT) and multispectral radiation thermometry (MRT). The exact spectral emissivity of an object must be known if the SRT is used to measure its temperature accurately. The prior knowledge of the relationship between the spectral emissivity and wavelengths is acquired when the DWRT or MRT is used to evaluate the accurate temperature of an object. However, the emissivity is influenced by a large number of variables, such as alloy compositions, surface characteristics (oxidation and roughness), process conditions, temperature, heating time and wavelength [3]. In high-temperature aero-engine environment, the alloys of turbine blades tend to be oxidized easily, and the emissivity change of the alloys will cause large errors in radiation thermometry. And the emissivity approaches to fixed values after the oxidation is saturated. Therefore, it is meaningful to study the change regularity of the emissivity of the Ni-based alloys for accurate temperature measurement of the blades. Besides, the measured emissivity of turbine blades can be used in calculating accurate temperature field of the turbine, in which the radiation must be taken into account.

In recent years, the emissivity of various metals and alloys with oxidation has been researched experimentally and theoretically.

* Corresponding authors at: Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China.
E-mail addresses: lixunfeng@iet.cn (X. Li), hxl@iet.cn (X. Huai).

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Mehling et al. [4] measured the infrared emissivity of various metals as a function of wavelength and angle of emission. They found that the oxidation of materials would result in a higher emissivity and an almost isotropic emissivity distribution. Kobayashi et al. [5] developed a system to measure the normal emissivity in vacuum and oxidizing environments, and the wavelength and temperature range were 0.55–5.3 μm and 780–1200 °C, respectively. A database of the normal spectral emissivity for thirty kinds of pure metals and alloys was built [6]. Furukawa and Iuchi [7] developed an apparatus to measure the spectral and directional emissivity in the controlled environment over the temperatures from room temperature to 1023 K. Then Iuchi [8] modeled the behaviors of directional and the polarized emissivity of metals during the growth of oxide films, which corresponded well with experimental results. Greene et al. [9] measured the total hemispherical emissivity of Inconel 718 for both unoxidized and oxidized samples as a function of sample temperature. They found that the emissivity of the oxidized samples showed a significant increase over the unoxidized samples. The emissivity of three Ni and Co based alloys was measured by del Campo et al. [10] to analyzed the effects of temperature, wavelength, emission angle and oxidation. They found the emissivity decreased with increasing wavelength independent of temperature and the oxidized samples had a higher emissivity. Wen et al. tested the spectral emissivity of aluminum [11,12] and steel [13,14] at several hundred Kelvin degree during oxidation and investigated the effects of wavelength, temperature, alloy composition and heating time on the spectral emissivity qualitatively. Shi et al. explored the relationships between the heating time and the emissivity of straight carbon steel [15], aluminum [16], red copper [17] and steel [18,19] during oxidation at high temperatures in air, and they developed analytical models to simulate the emissivity varied with time. Li et al. [20] measured the emissivity of Ti-6Al-4V alloy during oxidation process. The emissivity increased with the oxidation time below 873 K, and strong oscillation was observed above 923 K. Zhang et al. [21] measured the emissivity of pure titanium with the wavelength range of 3–27 μm, and the results showed that the emissivity increased with the increase of temperature and oxidation time and decreased with the increase of wavelength. Kong et al. [22,23] measured the emissivity of aeronautical alloys. It was found that the emissivity increased with the increasing temperature and the decreasing wavelength, and the oxidation enhanced the emissivity.

The oscillatory behavior of the emissivity during oxidation is an especial phenomenon of the emissivity. Some researchers [5–8,10,13–18,20–22] observed one or more strong emissivity oscillations in the experiment, but others [9–12,19] not. If the oscillations of the emissivity occurred, it would ultimately disappear when the oxidation film was optically thick enough. All the emissivity approached to fixed values after the saturation of the oxidation.

In previous works, most researchers only did the qualitative analysis rather than the quantitative analysis of the emissivity during oxidation and did not give a model of the emissivity. Furthermore, few researchers have studied the emissivity of the Ni-based alloys used for turbine blades during oxidation. And the temperature of the sample measured in relevant literatures mostly was under 700 °C. The main purposes of this paper are to study the quantitative change regularity of the normal spectral emissivity of three kinds of Ni-based alloys DZ125, DD6 and K465 during oxidation in air at different high temperatures, to compare the effects of the normal spectral emissivity and to model the emissivity versus heating time and wavelength. It is important to note that the emissivity models reported here are only valid for the same material with same experimental conditions. The models in the paper can be the references and modified to obtain the emissivity model with different experimental conditions or materials.

2. Experiment

2.1. Measurement principle

As is known to all, the maximum possible thermal radiative intensity at a given temperature is emitted by a blackbody, and the emissivity is defined by [24]

$$\varepsilon_\lambda(\lambda, T, \theta, \phi) \equiv \frac{I_\lambda(\lambda, T, \theta, \phi)}{I_{\lambda,b}(\lambda, T)} \tag{1}$$

where I_λ and $I_{\lambda,b}$ are the radiative intensity coming from a real surface and the perfect blackbody at the same temperature T and wavelength λ, respectively. θ and ϕ are the emitting zenith angle and azimuth angle, respectively (shown in Fig. 1). And the radiative intensity of the blackbody can be obtained from the Planck distribution

$$I_{\lambda,b}(\lambda, T) = \frac{2hc_0^2}{\lambda^5\{\exp[hc_0/(\lambda kT)] - 1\}} \tag{2}$$

where k is Boltzmann's constant, h is Planck's constant, and c_0 is the speed of light in vacuum.

The sample spectral intensity $I_{\lambda,meas}$ measured by a Fourier transform infrared (FTIR) spectrometer is composed of four components [11],

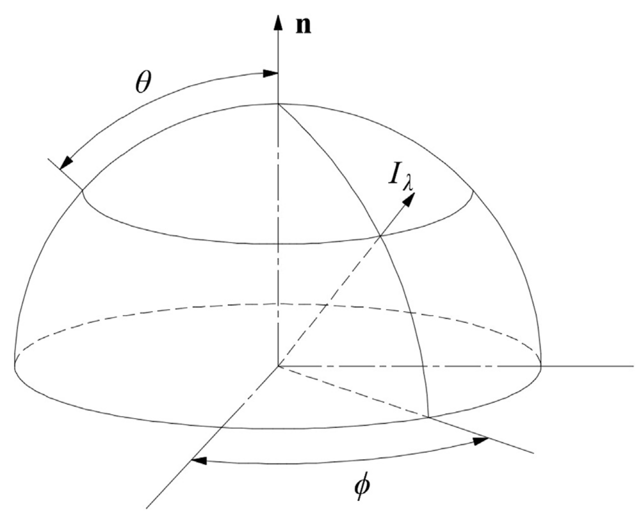

Fig. 1. Schematic of the emitting zenith angle θ and azimuth angle ϕ.

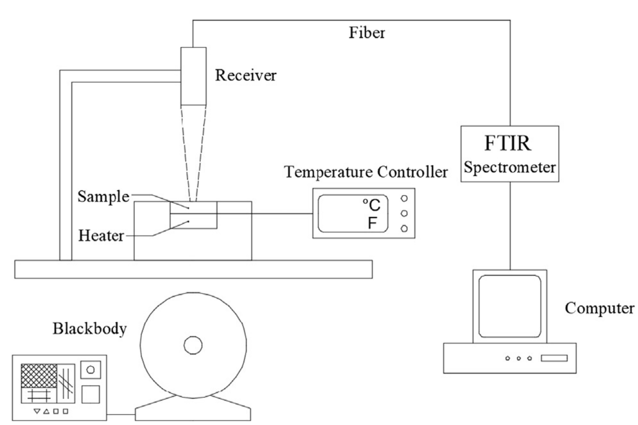

Fig. 2. Schematic of experimental system.