XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

EMISSIVITY-COMPENSATED RADIATION THERMOMETRY

T. Iuchi and T. Furukawa
Department of Mechanical Engineering
Toyo University, Kawagoe, Saitama 350-8585, Japan

Abstract: Emissivities of metals show large periodic type variation with the growth of the oxide film on their surfaces. The emissivitity variations are caused by the interference effect of radiation between the metal surface and the oxide film. In this paper, p-polarized and s-polarized emissivities as well as directional emissivities for a surface composed of metal and metallic oxide film are studied. From both theoretical and experimental considerations, the authors propose an emissivity-compensated radiation thermometry using a total radiometer that can provide an accurate way to avoid the interference effect on emissivity.
Keywords: Pyrometry, Emissivity, Polarization

1 INTRODUCTION

The change of emissivity of an object, for whatever reason, is a serious problem in radiation pyrometry, and has been the subject of much research [1~4].

In case of a metal, its emissivity widely changes with the growth of oxide film on its surface. This variation is caused by the interference effect of radiation between the metal surface and the oxide film.

The authors studied the directional and polarized spectral emissivities of metals during oxidation process theoretically and experimentally. As a result, we found that p-polarized and s-polarized emissivities as well as directional emissivities measured at different angles of a real metal surface behave in a different manner and depend strongly on the thickness of the oxide film. By utilizing these characteristics, we were able to develop the two radiation thermometry using spectral radiance, which got over the disturbance of the emissivity change caused by the interference effect [5~6].

These methods, however, are not useful when the thickness of the oxide film on the metal surface exceeds the sensitive wavelength of a monochromatic radiometer. If a total radiometer covering the wide spectral range is used for the measurement instead of using a monochromatic radiometer, the interference effect is to be cancelled due to the averaging.

In this paper, the advantage of the usage of a total radiometer instead of a monochromatic radiometer is described.

2 INTERFERENCE EFFECT OF SPECTRAL EMISSIVITY

As a metal is heated, the oxide film is grown on its surface. Thus the emissivity of the metal surface increases with increasing thickness of oxide film, but its value changes in an oscillating manner. This phenomenon is called the interference effect of emissivity caused by the multiple reflection of radiation between the metal surface and the oxide film.

In this paper, cold rolled steel sheets are used as specimens. θ is an angle or a direction measured from the normal to the surface of the specimen.

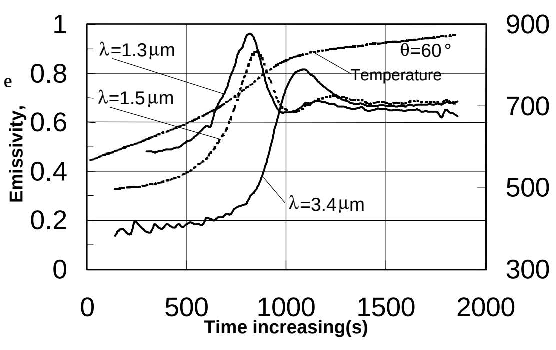


Fig. 1 Emissivity changes at λ=1.3,1.5,3.4µm with time increasing

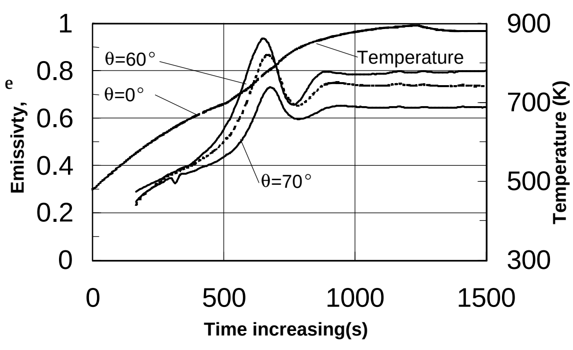


Fig. 2 Emissivity changes at θ=0°,60°,70° with time increasing

Fig.1 shows the experimental results of spectral emissivities of a specimen at the direction of θ=60° during heating in air. The temperature increase is plotted in this figure. The oscillating emissivities were observed at the wavelengths of 1.3, 1.5 and 3.4 µm, respectively. The time taken to reach the peak value increases with increasing wavelength.

Fig.2 shows the experimental results of spectral emissivities of a sample at the wavelength of 1.5 µm during heating in air. It is observed that the emissivities at the angles of θ=0°, 60° and 70° are oscillating, but the time taken to reach the peak value is delayed with increasing angle θ.

Fig.3 shows the experimental results of directional emissivities, $\varepsilon(\theta_1)$ and $\varepsilon(\theta_2)$ of a sample at the wavelength of 3.4 µm and at the directions of θ_1=20° and θ_2=80° during heating in air. In the early stage of the oxide film growth on the metal surface, the emissivity $\varepsilon(\theta_2)$ at θ_2=80° is higher than the emissivity $\varepsilon(\theta_1)$ at θ_1=20°, but the emissivity at θ_1=20° becomes higher than the emissivity at θ_2=80° with increasing thickness of oxide film.

Fig.4 shows the experimental results of s-polarized spectral emissivities, $\varepsilon_s(\theta)$ of a specimen at the angle of θ=60°. The oscillating changes of the polarized, spectral emissivities at the wavelengths of 1,3, 1,5, 3.4 and 5.3 µm caused by the interference effect appear in a similar manner as in Fig.1. The changes are delayed with increasing wavelength.

The ratio $R_e=\varepsilon(\theta_2)/\varepsilon(\theta_1)$ of the directional spectral emissivities at a specified wavelength λ and the ratio $R_{ps}=\varepsilon_p(\theta)/\varepsilon_s(\theta)$ of the polarized spectral emissivities at a specified direction θ and a specified wavelength λ have been shown experimentally to depend strongly on the thickness of the oxide film. These ratios are closely related to a specified emissivity.

Fig.5 (a)~(d) show some characteristic curves between the ratio R_e of the radiances that are

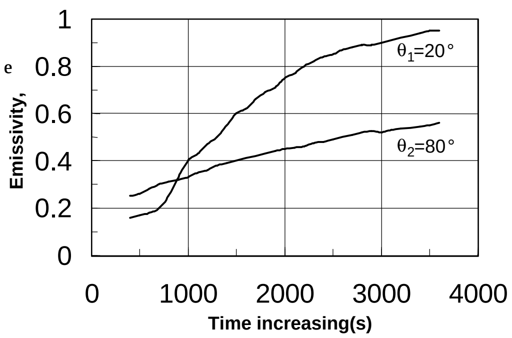


Fig. 3 Directional emissivity at different angles, θ_1 and θ_2

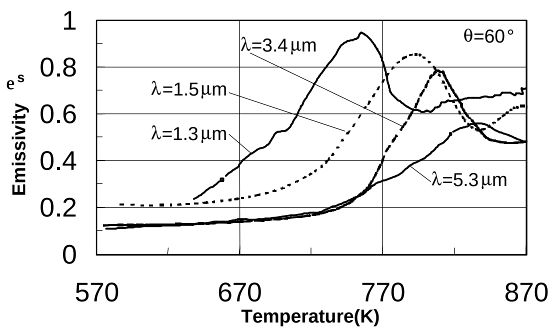


Fig. 4 Interference effect on s-polarized emissivity

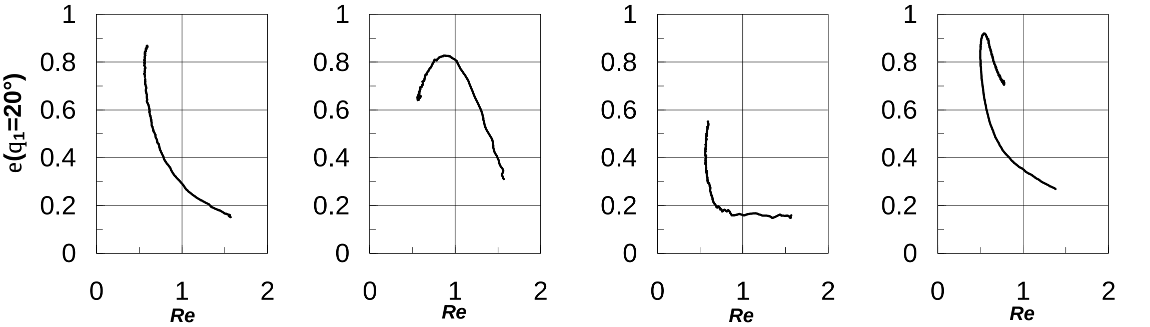
measured at θ_1=20° and θ_2=60°, and the directional spectral emissivity $\varepsilon(\theta_1)$ measured at θ_1=20°. (a)~(d) of Fig.5 represent the combinations of wavelengths used for the measurement of the ratio R_e and the directional spectral emissivity $\varepsilon(\theta_1)$ [5]. In case of (a) and (b), there are the good relations between R_e and $\varepsilon(\theta_1)$ as far as the thickness of the oxide film does not exceed some amount of quantity. From these relations, the compensated emissivity $\varepsilon(\theta_1)$ can be obtained by measuring R_e. In case of (c) and (d) in Fig.5, there are two solutions of $\varepsilon(\theta_1)$ for the measurement of R_e. Therefore, these relations are not applicable. The emissivity-compensated radiation thermometry using directional spectral emissivities at different angles is limited because of the interference effect of radiation as far as the spectral radiances are used for the measurement as shown in Fig.5.

Fig.6 (a)~(d) also show some characteristic curves between the ratio R_{ps} measured at θ=60° and the normal spectral emissivity measured where (a)~(d) represent the combinations of wavelengths used for the measurement of the ratio R_{ps} and the normal spectral emissivity $\varepsilon(\theta=0°)$ [6]. In case of (a) and (b) in Fig.6, there are the good relations between R_{ps} and $\varepsilon(\theta=0°)$ as far as the thickness of the oxide film does not exceed some amount of quantity, which are the similar features shown in Fig.5 (a) and (b). From these relations, the compensated emissivity $\varepsilon(\theta=0°)$ can be obtained by measuring R_{ps}. In case of (c) and (d), there are two solutions of $\varepsilon(\theta=0°)$ for the measurement of R_{ps}. Therefore, these relations are not applicable. The emissivity-compensated radiation thermometry using polarized spectral emissivities at a specified direction and a specified wavelength is limited as far as the spectral radiances are used for the measurement. This is the same situation as in Fig.5.

For both methods using spectral radiances, the following items are necessary in order to negate the interference effect of the oxide film.

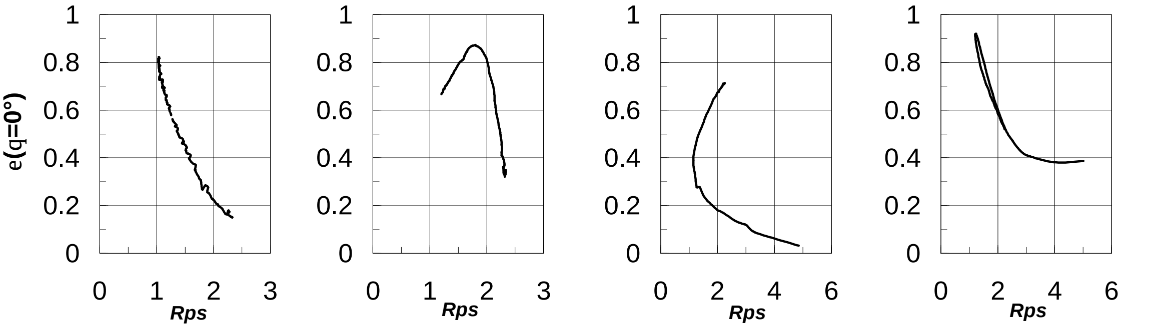
(1) R_e and R_{ps} should be measured at as long a wavelength as possible.

(2) Emissivities to be compensated should be measured at a wavelength equal to or shorter than the wavelength used for the measurements of R_e and R_{ps}.



(a) ε(θ1=20°) at λ=3.4μm, *Re* at λ=3.4μm (b) ε(θ1=20°) at λ=1.5μm, *Re* at λ=3.4μm (c) ε(θ1=20°) at λ=3.4μm, *Re* at λ=1.5μm (d) ε(θ1=20°) at λ=1.5μm, *Re* at λ=1.5μm

Fig.5 Characteristic curves between *Re* and directional emissivity ε(θ1=20°)



(a) ε(θ=0°) at λ=3.4μm, *Rps* at λ=3.4μm (b) ε(θ=0°) at λ=1.5μm, *Rps* at λ=3.4μm (c) ε(θ=0°) at λ=3.4μm, *Rps* at λ=1.5μm (d) ε(θ=0°) at λ=1.5μm, *Rps* at λ=1.5μm

Fig.6 Characteristic curves between *Rps*(θ=60°) and nomal emissivity ε(θ=0°)

3 MEASUREMENT BY TOTAL RADIOMETERS

The experiments and considerations have been conducted so far from the standpoint of the measurement of spectral radiances. The oscillating change of the emissivity seems to occur with the growth of the oxide film on a metal surface at any spectral radiation. If a total radiometer covering the wide spectral range is used for the measurement of total radiance, the oscillating variation of the emissivity caused by the interference effect will be possibly averaged and disappear. This is the topic of this paper.

Fig.7 is a schematic diagram of an experimental apparatus for the simultaneous measurements of spectral ant total emissivities of a specimen. A monochromatic radiometer using an InGaAs sensor with an optical filter of 1.5 μm and a total radiometer using a thermopile sensor with a CaF_2 filter transparent to the wide spectral range from 1 to 10 μm are set at the angle of 60°, respectively. The temperature of a specimen is measured by a K-type thermocouple welded on the surface of the specimen. The spectral and total radiances are measured simultaneously by the monochromatic and the total radiometers, respectively during heating in air. The spectral and total emissivities are calculated using the measured radiances and the blackbody radiances derived from the temperature of the specimen.

Fig.8 shows the experimental results of the measurement of the emissivity variation of a sample using the apparatus in Fig.7. As shown in this figure, the spectral emissivity shows an oscillating change with increasing temperature, however, the total emissivity as predicted increases monotonously during heating.

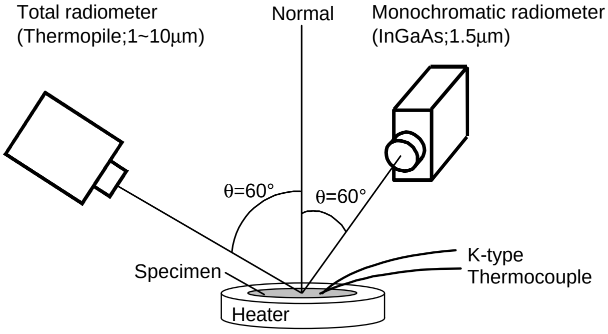


Fig.7 Experimental apparatus for the simultaneous measurements of spectral and total emissivities

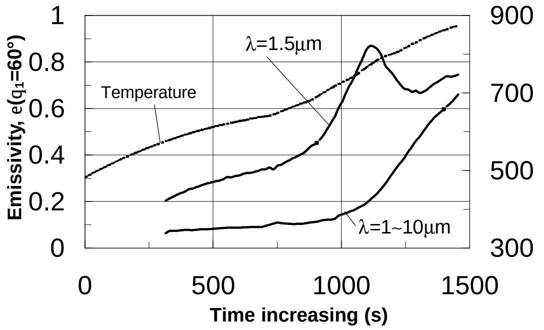


Fig.8 Variations of spectral and total emissivities

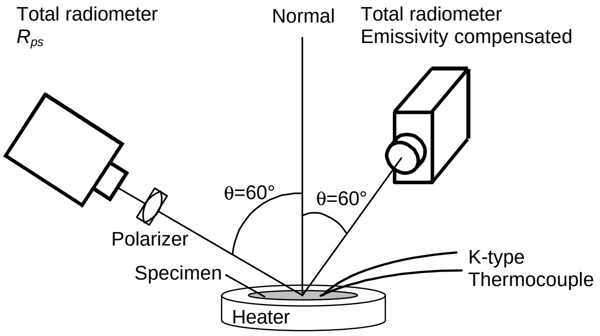


Fig.9 Experimental apparatus for the simultaneous measurements of R_{ps} and total emissivity

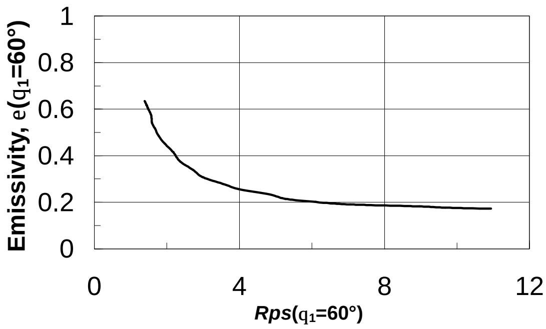


Fig.10 Experimental relation between R_{ps} and total emissivity to be compensated

Fig.9 is an apparatus for the measurement of a characteristic curve between the ratio R_{ps} and the total emissivity. Two total radiometers with the same specifications of the total radiometer used in Fig.7 are set at the angle of θ=60°, respectively. The one of them is used to measure the ratio R_{ps} and the other is utilized to measure the total emissivity of a specimen. A KRS-5 infrared polarizer is inserted in front of the former radiometer and by rotating the polarizer, p- and s-polarized radiances are measured sequentially so that the ratio R_{ps} is obtained. The procedure to calculate the emissivity of a specimen is similar to the case of Fig.7.

Fig.10 is an experimental relation between R_{ps} and the total emissivity for a cold rolled steel sheet. This relation can be applied to an emissivity-compensated radiation thermometry in which by measuring the ratio R_{ps}, the total emissivity to be compensated is derived from the relation between R_{ps} and the emissivity.

Fig.11 shows the reproducible results of the characterisitic curve of Fig.10 where 22 specimens of cold rolled steel sheets were used for the measurement. Although the total emissivities change from 0.17 to 0.75 during heating, the relative errors of the emissivity $|\Delta\varepsilon/\varepsilon|$ and the temperature $|\Delta T/T|$ are 0.05 and 0.012, respectively.

The usage of the total radiometers for the emissivity-compensation method is powerful enough to negate the interference effect of the emissivity, but the compensation of a spectral emissivity at a shorter wavelength may be much more advantageous than the usage of the total emissivity from the point of the accuracy of the temperature measurement as shown in Fig.12 because even though a shorter spectral emissivity change periodically with the growth of the oxide film on the surface of a specimen, the ratio R_{ps} measured by a total radiometer reduces monotonously with the growth of the oxide film. Therefore, it is an urgent work to confirm the advantage of the combinations of the usage of a total radiometer for the measurement of R_{ps} with the usage of a monochromatically shorter radiometer for the emissivity compensation.

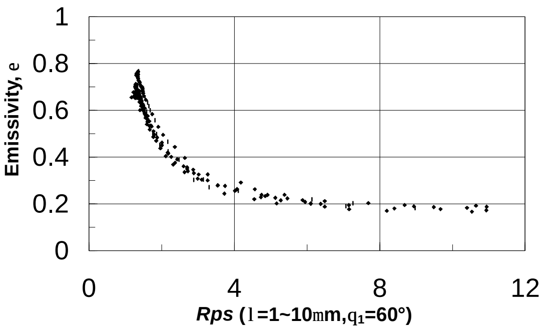


Fig.11 Reproducible results of the relation between *Rps* and total emissivity to be compensated

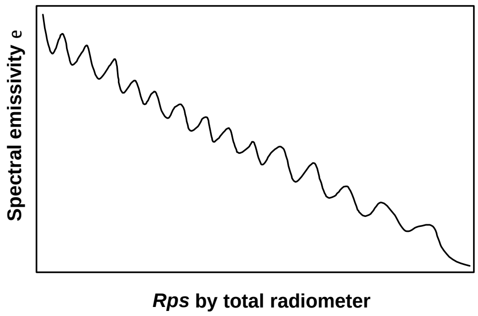


Fig.12 Predicted relation between *Rps* measured by total radiometer and spectral emissivity to be compensated

4 CONCLUSION

An emissivity-compensated radiation thermometry utilizing the characteristic curve between R_{ps}, the ratio of the total p- and s- radiances and the total emissivity has been shown to be valid for negating the interference effect of emissivity. The characteristic curve between R_e, the ratio of the directional total emissivities and the total emissivity has not been investigated yet in this paper. This is another study to be done.

Although a total radiometer so far has been assumed to be unsuitable for the temperature measurement because the so called n-value is roughly 4 which means quite low, the usage of total radiometers can reevaluate from the viewpoint of avoiding the interference effect of radiation.

This research is funded by the Ministry of Education, Science, Sports and Culture under Grand-in-Aid for Scientific Research (C) (project number 10650416).

REFERENCES

[1] C.P. Tingwaldt and H. Magdeburg, A new optical method for the determination of thermodynamic temperatures of glowing metals, TEMPERATURE, **3**, (1962) 483-486

[2] T.P. Murray, The polarized radiation method of radiation thermometry, TEMPERATURE, **4**, (1972) 619-623

[3] T. Iuchi and R. Kusaka, Two methods for simultaneous measurement of temperature and emittance by using multiple reflection and specular reflection, and their applications to industrial processes, TEMPERATURE, **5**, (1982) 491-503

[4] F. Tanaka and H. Ohira, Thermometry reestablished by automatic compensation of emissivity, The TRACE method, TEMPERATURE, **6**, (1992) 895-900

[5] T. Iuchi and T. Tsurukawaya, New radiation thermometry using directional emissivity in P. Marcarino(ed.), Proceedings of TEMPMEKO'96 (Torino Italy, 10-12. September 1996), 1996, p.359-364

[6] T. Iuchi, T. Furukawa and T. Tsurukawaya, Measurement of polarization properties of metals and its application to radiation thermometry in J.Halttnen(ed.), Proceedings of 14^{th} IMEKO, **6**,(Tampere, Finland, 1-6. June 1997), 1997, p.108-113

AUTHORS: Department of Mechanical Engineering, Toyo University, 2100 Kujirai, Kawagoe, Saitama 350-8585, Japan, Phone +81 492 39 1326, Fax +81 492 33 9779, E-mail: Iuchi@eng.toyo.ac.jp