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Emissivity-Free Thermometer Using Principal Component Analysis and Its Application

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Abstract:

Various heating processes are used in a steel works. However, emissivity compensation is still one of the most difficult problems when radiation thermometers are applied to temperature measurements of heated sheets in steel manufacturing processes. JFE Steel proposes a new technique using spectral information of radiation from targets and principal component analysis (PCA). Temperatures are calculated from the principal component which is predetermined so that its scores change with temperature and are minimally affected by the deviation of spectral emissivity. The developed thermometer was installed at an annealing furnace in the stainless steel manufacturing process. As a result, it was found that the standard deviation and the maximum error of the developed radiation thermometer from the values measured by thermocouples were less than those of an ordinal single-wave thermometer.

1. Introduction

Because temperature is one of the critical parameters which determine the properties of steel products, temperature measurements are performed at various points in steel manufacturing processes. As temperature measurement technologies for steel strips in the cold rolling and coating processes, thermometer rolls [1)] using the assumption that temperature of the roll and the steel strip are the same, and multiple reflection type radiation thermometers [2)], which utilize the wedge between the roll and strip, are used in measurements at points where the strip in wound around a roll. However, these technologies cannot be applied to measurement in sections where the strip travels in a horizontal or vertical path. In environments where emissivity is not an issue, general-purpose radiation thermometers are used after first setting emissivity, but accurate strip temperature measurement is not possible in environments such as annealing furnaces, etc. where emissivity deviation occurs. Because there are also many other steel manufacturing processes where accurate temperature measurement is impossible due to emissivity deviation, development of a radiation temperature measurement technology which is not affected by emissivity deviation had been desired.

Against this background, JFE Steel proposed and developed a new measurement method to realize accurate temperature measurement in environments with emissivity deviation [3)]. As a feature of the new method, the light radiated from the measurement target is measured, and a multivariate analysis technique such as principal component analysis (PCA) is applied to the spectral radiation acquired by spectrally dispersing the radiated light. Concretely, a spectral component which is minimally affected by emissivity deviation is obtained in advance by multivariate analysis, and the temperature is then calculated from the score of that spectral component, which is included in the radiation spectrum of the measurement target, by using a predetermined calibration curve. The spectral component which is minimally affected by emissivity deviation is obtained by using a vector with a condition orthogonal (inner product; that is, the product sum of the wavelength components is zero) to the deviation of spectral emissivity, which has been evaluated in advance by PCA, etc.

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This paper describes the principle of the new measurement method (hereinafter, spectral principal component thermometer) and reports an example of its application to an actual production line.

2. Issues of Radiation Temperature Measurements and Features of Developed Technology

The measured spectrum L (λ, T) obtained with radiation thermometers that measure the conventional radiation temperature T (K) is the product obtained by multiplying the spectral radiance (energy) L_B (λ, T) of a blackbody by emissivity ε (λ), as shown in Eq. (1).

$$L(\lambda,T)=\varepsilon(\lambda)\cdot L_B(\lambda,T) \quad \text{.....................} (1)$$

where, λ is wavelength and L_B (λ, T) is Planck's law given by Eq. (2).

$$L_B(\lambda,T)=\frac{2c_1}{\lambda^5}\frac{1}{\exp\left(\frac{c_2}{\lambda T}-1\right)} \quad \text{..................} (2)$$

where, c_1, c_2 are physical constants.

In the case of the conventional radiation temperature measurement, the temperature is obtained by solving the equation in (1) on the assumption, for example, that ε (λ) is constant in the case of a single-wave thermometer, and that ε (λ_1) = ε (λ_2) for the emissivity of measured wavelengths λ_1 and λ_2 in a double-wave thermometer. However, temperature error may occur because these hypotheses are not strictly materialized.

In this paper, radiation temperature (λ, T) is described in a divided form, in that emissivity ε (λ) is expressed by an assumed value of emissivity ε_0 (λ), which is posited in advance, and the variable component of emissivity, which can change depending on operating conditions or other factors, is expressed by a multiplier g (λ):

$$L(\lambda,T)\equiv\varepsilon_0(\lambda)\cdot g(\lambda)\cdot L_B(\lambda,T) \quad \text{..............} (3)$$

If both sides of Eq. (3) are deformed by taking their logarithms, Eq. (4) is obtained.

$$\log L_B(\lambda,T)=\log\left(L(\lambda,T)/\varepsilon_0(\lambda)\right)-\log g(\lambda) \quad \text{..} (4)$$

Although there is a possibility that the log L_B (λ, T) calculated by the right side of Eq. (4) may include error originating from g (λ), the form that log L_B (λ, T) can take is inherently determined as shown by Eq. (4). Therefore, it was thought that the true form of log L_B (λ, T) can be estimated by using the fact that the form of log g (λ) is different from that form.

In Eq. (3), it is supposed that ε_0 (λ), for example, is the average spectrum of variable emissivity, and g (λ) is the deviation from that average value. Therefore, if it is assumed that ε_0 (λ) ≡ 1, it is also possible that all emissivity deviations may be included in g (λ). However, if the average spectrum of emissivity is used as ε_0 (λ), the features of the spectra of emissivity deviations can be grasped more accurately, and the true form of L_B (λ, T) can be estimated.

When using the conventional radiation temperature, an appropriate wavelength was selected corresponding to the measurement target and temperature, but in this study, a wider wavelength region was actually measured, and the spectral shape was obtained by spectroscopy. PCA was studied as a technique that focuses on this spectral form. The following chapter presents a detailed explanation of the application of PCA.

3. Application of Principal Component Analysis to Radiation Thermometry [3)]

3.1 Principal Component Analysis

First, PCA will be explained [4)].

As an example, consider a distribution map of the height and weight of the members of a certain group, as shown in **Fig. 1**. Because it can generally be said that taller persons also weigh more, this distribution map has a positive slope of the distribution. The diagonal line rising to the right inserted in the figure passes through the center of this distribution and is, as it were, a measure of "body size." PCA is a technique for statistically deriving a representation of the essential interpretation of this combined data of height and weight (2-dimensional) by a 1-dimensional scale, in this case, "body size." Although the example in Fig. 1 concerns 2-dimensional data, this technique has the effect of reducing dimensionality as the original number of dimensions of the data becomes larger.

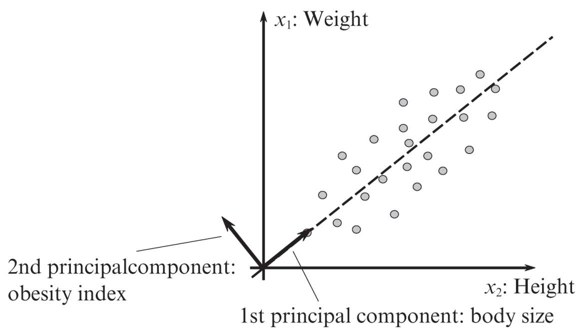


Fig. 1 Distribution map of the weight and the height and principal components

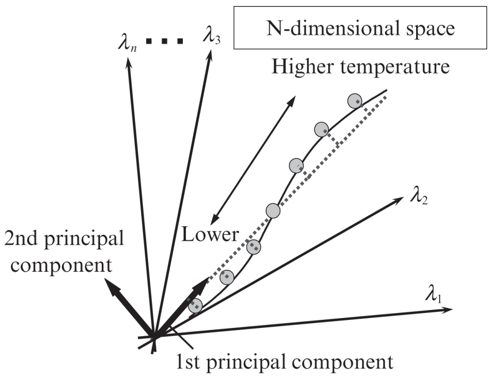


Fig. 2 Schematic of n-dimensional description of spectral radiation and its principal components

Expressed mathematically, the "body size" in this example is the 1st principal component, and the next essential information following this 1st principal component, which is orthogonal to the 1st principal component, is the 2nd principal component. In physical terms, the 2nd principal component in Fig. 1 is a scale called the "obesity index."

3.2 Application of Principal Component Analysis to Radiation Spectrum

In the example in Fig. 1, the original 2-dimensional information (height and weight) is reduced to 1-dimensional information, i.e., "body weight," by PCA. If this information processing technique for extracting the essence is applied to the spectral waveform in temperature estimation, the essential changes in the radiation spectrum accompanying temperature changes can be extracted from the information of a number n of wavelengths. In this case, as shown in **Fig. 2**, the wavelength information (spectrum) for a wavelength n is expressed as one point in an n-dimensional space having the same number of dimensions as the number n of measured wavelengths. For example, assuming that spectral radiation data of n wavelengths are given for 7 temperatures, 7 points are given in the n-dimensional space. Considering the spread of the distribution of these 7 points in the n-dimensional space, the direction with the largest spread is defined as the direction of the 1st principal component. This is the most essential information for differentiating the above-mentioned 7 points, that is, for differentiating temperatures.

Next, let us try actually applying PCA to spectral radiance data. PCA is applied to the result (**Fig. 3**(b)) of performing a log operation on the spectral radiance of a blackbody $L_B(\lambda, T)$ obtained by measuring a blackbody furnace with temperatures of 7 levels from 500°C to 800°C shown in Fig. 3(a) and, for example, the 1st and 2nd principal components are obtained. This low-dimensional principal component information is the essential spectral information (spectral component) of the initial 7 items of spectral information for the blackbody radiation energy.

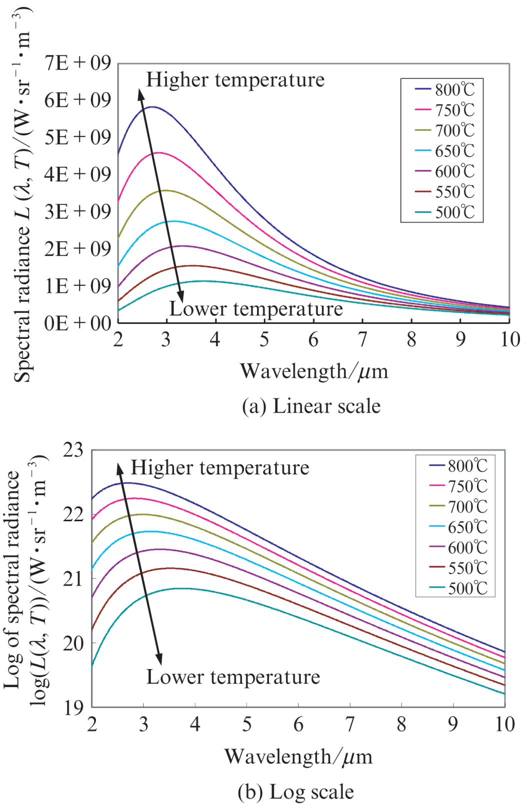
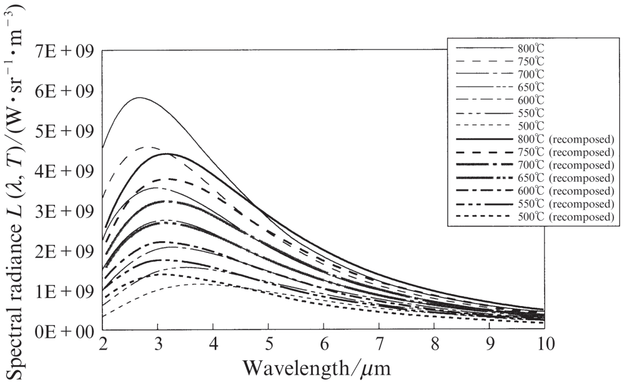


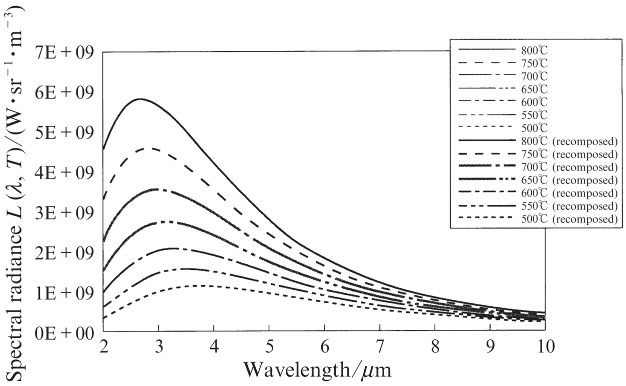
Fig. 3 Spectral radiance from black body

In order to verify that this low-dimensional principal component information is in fact the essential spectral information (spectral component) of the initial 7 items of spectral information, the initial spectral radiation for the 7 temperature levels was recomposed from the spectral component. **Figure 4** shows the degree of fit obtained by recomposition of the spectral radiation. Here, recomposition means a product sum calculation, that is, a linear operation, in which the base vector is multiplied by a constant factor, and in case of multiple base vectors, the base vectors multiplied by the constant factor are added together. The coefficient of this process is called a score, and is obtained by calculating the inner product of the initial waveforms and their respective base vectors (integrated by totaling for each wavelength).

The degree of fit after recomposition changes depending on the degree of correspondence of the low-dimensional base vector information to the initial 7 optical spectra. Fig. 4(a) shows the result of recomposition by only the 1st principal component, and Fig. 4(b) shows the result of recomposition including the 2nd principal component. It can be understood that all 7 optical spectra are recomposed extremely well if the 2nd principal component is also used. In other



(a) Recomposition by only 1st principal component



(b) Recomposition by 1st and 2nd principal component

Fig. 4 Recomposition of spectral radiation using principal components

words, this means that it is not necessary to express each optical spectrum by wavelength information for n points, i.e., the coordinates for n dimensions, but rather, if two base vectors are decided in advance, this can be expressed simply by the two points of information (scalar quantity) of two coefficients (scores) for its linear sum. To put it yet another way, it can be said that n-dimensional data were compressed to 2-dimensional data. Although the number of dimensions is greatly reduced by the process, it is important that the spectral radiation is recomposed by the essential spectral waveform, that is, the “base vector.”

Using this fact, the following considers a method that is minimally affected by external disturbances, i.e., emissivity deviation, as described previously.

3.3 Proposal of Spectral Principal Component Radiation Thermometer Unaffected by Emissivity Deviation

Section 3.2 described the basic concept of PCA of optical spectrum data. The following further considers a method for applying PCA in order to avoid the effect of emissivity deviation of the measurement target. In the above Eq. (2), it is assumed that the behavior of the emissivity deviation g (λ) of the measurement target is known in advance, and a PCA of that emissivity deviation data is carried out to obtain the principal components of that emissivity deviation. Here, the obtained principal component of emissivity deviation expresses the statistical behavior of the emissivity deviation of the measurement target. Conversely, it can be said that the vectors orthogonal to the principal component vector of emissivity deviation are all virtually unaffected by emissivity deviation.

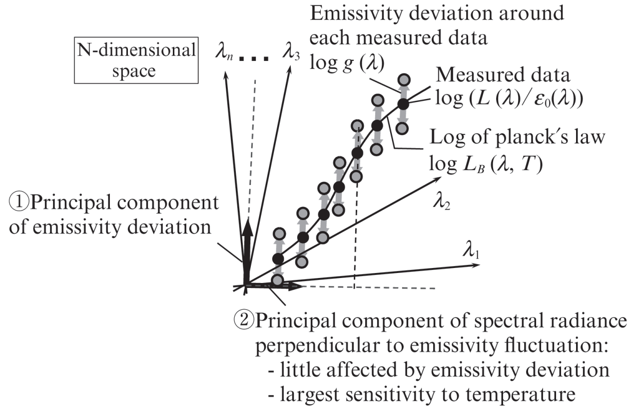


Fig. 5 Schematic concept of new thermometry technique using principal components

Therefore, the essential information of reaction energy can be extracted, virtually unaffected by emissivity deviation, by performing a PCA of spectral radiance, under the restriction that it must be orthogonal to the principal component of emissivity deviation. As the concrete procedure, after removing the principal component of emissivity deviation from the spectral radiance spectrum in advance, PCA is conducted by the normal method. If a normal PCA can be conducted, the principal components that are obtained will, in all cases, be orthogonal to the principal component of emissivity deviation.

Accordingly, a temperature measurement method which is minimally affected by emissivity deviation can be realized by focusing on the principal component of the radiation energy orthogonal to the principal component of emissivity deviation, and using the spectral radiance spectrum and the score of its principal component.

This will be explained using **Fig. 5**. Planck’s law is expressed as one curved line in an n-dimensional space, as shown in Fig. 5. If the measured spectrum L (λ, T) and the emissivity spectrum ε_0 (λ) are obtained accurately, L (λ, T) / ε_0 (λ) should be positioned on that curve. However, in reality, the results will be measured at positions that deviate from the curve due to the deviation g (λ) of emissivity, resulting in temperature error. Thus, if the principal component of emissivity deviation g (λ) is obtained (① in Fig. 5) temperature measurement that is minimally affected by emissivity deviation will become possible as the number of principal components of spectral radiance (② in Fig. 5) orthogonal to the principal component of g included in the measured data becomes larger.

4. Example of Application to Actual Equipment

4.1 Measurement of Strip Temperature in Annealing and Pickling Line for Stainless Steel

The annealing and pickling line for stainless steel is a line which performs annealing and pickling of cold-rolled stainless steel strips. Although control of the strip temperature is important for building quality into products, accurate measurement of the strip temperature with conventional radiation thermometers was not possible due to the emissivity deviation caused by growth of an oxide film on the strip surfaces during annealing.

Therefore, in the past, annealing cycle design (design of the furnace temperature pattern) was performed by using the strip temperature estimated by a heat transmission model calculation. For this reason, the allowable range of strip thickness changes and changes in the furnace temperature pattern were set conservatively, because there was a high possibility that the strip temperature would exceed the allowable range in the transient state during changes in the strip thickness or furnace temperature pattern. In cases where the strip temperature exceeded this allowable range, material quality defects were avoided by passing dummy strips, but the decrease in productivity due to use of dummy strips was an problem.

To solve this problem, the authors studied application of the spectral principal component thermometer to the stainless steel annealing and pickling line. The effectiveness of this technology was verified by simulations, sample tests and actual equipment tests, and the thermometer was installed as actual equipment [3, 5–7].

4.2 Equipment Outline [8]

The spectral principal component thermometer and a contact-type thermometer were installed at the exist side of the heating zone of the annealing furnace. The configuration of the spectral principal component thermometer and the outline of the equipment are shown in **Fig. 6** and **Fig. 7**, respectively. The hardware of the spectral principal component thermometer comprises mainly a CCD camera, spectrometer and lens. The spectrometer contains slit and prism-grating-prism dispersive elements, and spectral diffraction is done by passing light through these elements. The CCD camera

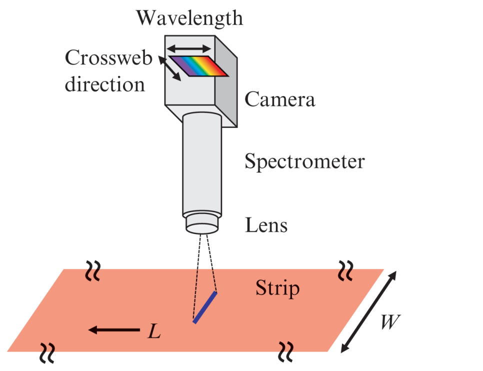


Fig. 6 Configuration of developed thermometer

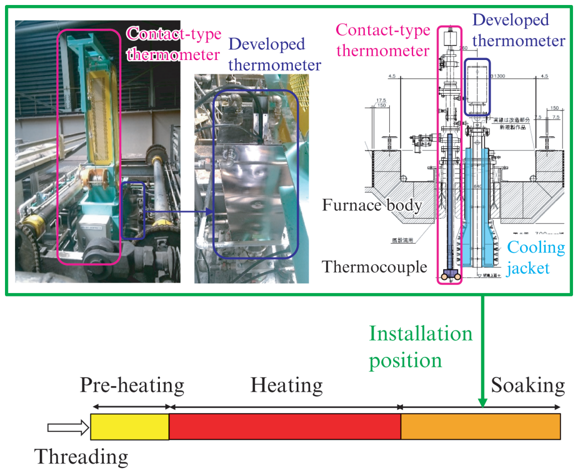


Fig. 7 Actual equipment of manufacturing line

is a system which scans one dimension as the width direction of the steel strip and measures wavelength information in the other dimension. The information for the width direction is averaged, and only one point is output as spectral radiation.

With the contact-type thermometer, the strip temperature is measured by intermittently pressing a thermocouple against the steel strip. This thermometer is used to acquire data for determining the principal component which is to be used, and also in periodic calibrations.

The actual temperature measurement procedure is as follows: First, the spectral radiation of a blackbody furnace corresponding to multiple temperatures is measured off-line in advance. Next, as much data as possible on the temperatures and their corresponding spectral radiation is acquired by using the contact-type thermometer, and the average emissivity, emissivity deviation and their principal components are calculated from the acquired data. Following this, a second principal component analysis of the spectral radiation of the blackbody furnace is conducted, this time excluding the principal component of emissivity deviation. The principal components to be used in temperature mea-

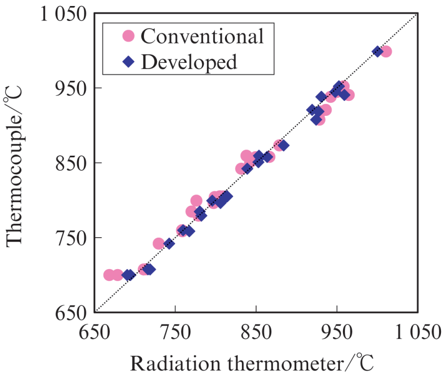


Fig. 8 Comparison of temperatures measured by developed and conventional thermometers

surements are decided, and a calibration curve is prepared based on the relationship between the principal component scores and temperatures. This procedure enables continuous measurement of the strip temperature by the spectral principal component thermometer.

4.3 Results

Data were collected using the contact-type thermometer, and the principal components to be used were adjusted based on those data. A calibration curve was prepared using only the wavelength of 0.9 μm and the measured temperature values calculated using the principal components, and the measured values obtained with a conventional single-wave thermometer and the developed spectral principal component thermometer were compared. In this comparison, the emissivity of the conventional thermometer was set to minimize error, and measured values of the developed thermometer were calculated in the same manner. The results of this comparison are shown in **Fig. 8**. Although the maximum error of the spectral principal component thermometer was 18.6°C with a standard deviation σ = 7.2°C, the maximum error and standard deviation of the conventional single-wave radiation thermometer were 31.6°C and σ = 13.1°C, respectively. Thus, this experiment demonstrated that the maximum error of the spectral principal component thermometer is far smaller than that of the conventional single-wave thermometer.

Based on these results, the spectral principal component thermometer was applied in the standard manufacturing process. **Figure 9** shows the results of the strip temperature and mechanical property tests during a certain annealing cycle change. Following the material change, the result of the mechanical property test was failure in the portion where the temperature increased, confirming the relationship between the strip

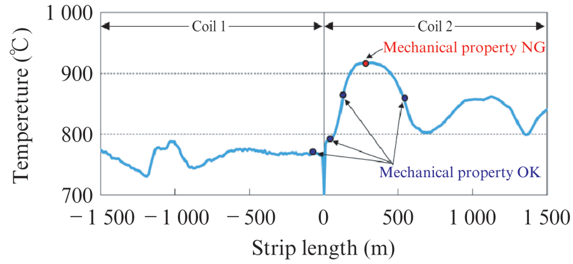


Fig. 9 Change of annealing conditions in test of developed thermometer

temperature and material property test results. Control standards were set through this series of experiments, and quality control by the actual strip temperature has now become possible, even during cycle changes.

5. Conclusion

A new temperature measurement technique using spectral radiance and multivariate analysis, which is minimally affected by emissivity deviation, was proposed. The developed thermometer was installed in the annealing furnace of a stainless steel annealing and pickling line, and the results confirmed that maximum error and standard deviation were both smaller than with the conventional single-wave radiation thermometer. In the future, development of this technology to other steel manufacturing processes is planned.

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