DEVELOPMENT OF TECHNOLOGY FOR HIGH-ACCURACY TEMPERATURE MEASUREMENT OF CLINKER IN KILNS: PART 2 — IMPROVEMENT OF MEASUREMENT ACCURACY FOR PRACTICAL APPLICATION

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ABSTRACT: High-accuracy temperature control during clinker burning is important for reducing energy consumption in cement production. Although a radiation thermometer is conventionally used for temperature measurement of clinker, it suffers from the problem that the measurement accuracy is reduced by the influence of dust in the kiln. We therefore propose a measurement method that eliminates the influence of dust by using a separate radiation thermometer for measuring the dust temperature. However, this method suffers from the problem of measurement error when the dust concentration and temperature are non-uniform. To further improve measurement accuracy, we devised a method for measuring clinker temperature by using two radiation thermometers aimed at the clinker and a nose-ring plate attached to the outer circumference of the kiln exit. When this method was applied to an existing kiln, the measurement error was found to be -10 to 25 °C, confirming that the accuracy was greatly improved over the conventional method.

KEYWORDS: Temperature measurement, Clinker, Cement kiln, Low-temperature burning, Dust-canceling method, Radiation thermometer, Two-color temperature

1. INTRODUCTION

Energy saving in the clinker burning process, which consumes the most energy in the cement manufacturing process, is an important issue. The clinker burning temperature as measured by radiation thermometer is used as an index for determining the amount of thermal energy input to the kiln in energy resources such as coal or similar, but the measurement error due to dust in the kiln is too large for precise control. In low-temperature burning techniques using a mineralizer1, 2), there is concern that the measurement accuracy may become even lower due to further increase in the amount of dust. Even if the burning temperature is lowered by applying the technique, the operation temperature cannot be kept significantly lower than the normal operation and energy savings may not be obtained. To solve this problem, we proposed the dust-canceling (DC) method that can eliminate the influence of dust in Part 1 of this work “Theory of the dust-canceling method and application to an existing kiln”3). This method corrects the clinker temperature by using a radiation thermometer for measuring dust temperature in addition to the usual radiation thermometer for measuring clinker temperature. However, the optical paths for measuring dust and clinker are different in this method, so significant error may result from differences in dust concentration and temperature between the paths.

To solve this problem, we propose an improved DC (IDC) method. In this method, two radiation thermometers are used for measuring the clinker and dust. The clinker temperature obtained is corrected by the radiation thermometer for dust that faces a nose-ring plate, which is attached to the outer circumference of the kiln exit relatively close to the clinker so that the optical paths of both radiation thermometers are almost identical. In this report, we describe the theory, wavelength selection for improving measurement accuracy, measurement in an existing kiln, and measurement results for accuracy verification.
2. THEORY OF TEMPERATURE MEASUREMENT

2.1 Measurement theory of radiation thermometers

A radiation thermometer is a device that measures temperature by detecting the energy of the light emitted from the object to be measured. The energy \( \langle L \rangle \) of the light emitted from the object depends on the temperature of the object and is expressed by Planck’s law (Eq. [1]).

\[
L = \frac{2C_1}{\lambda^3} \frac{1}{\exp \left( \frac{C_2}{\lambda T} \right) - 1}
\]

where:
- \( C_1 \): First radiation constant
- \( C_2 \): Second radiation constant
- \( T \): Temperature of the object
- \( \lambda \): Wavelength used for measurement

This can be rewritten as follows:

\[
T = \frac{C_2}{\lambda} \frac{1}{\ln \left( 1 + \frac{2C_1}{\lambda T} \right)}
\]

The radiation thermometer measures the temperature by substituting the detected energy into Eq. [1’]. Furthermore, there is a two-color temperature method that uses two wavelengths (\( \lambda_1, \lambda_2 \)) to measure the temperature as given by Eq. [2]. The two-color temperature method offers higher measurement accuracy than the single wavelength method.

\[
T = \frac{C_2 (1/\lambda_2 - 1/\lambda_1)}{\ln (L_{\lambda_1}/L_{\lambda_2}) + 5\ln (\lambda_1/\lambda_2)}
\]

To devise an equation for solving the clinker temperature, the propagation of light under the influence of the dust must be considered. The propagation of light from the measured object to the radiation thermometer is described by the radiative transfer equation \(^{15} \) (Eq. [3]).

\[
\frac{dL'}{ds} = -(a + \sigma) L + a e_{dus} L_{dus} + \frac{\sigma}{4\pi} \int L' \Phi d\Omega
\]

where:
- \( L' \): Spectral radiance incident from surroundings
- \( L_{dus} \): Spectral radiance of dust
- \( e_{dus} \): Emissivity of dust cloud
- \( a \): Absorption coefficient of dust particles
- \( \sigma \): Scattering coefficient of dust particles
- \( \Phi \): Phase function

The first term on the right-hand side represents the attenuation due to dust absorption and scattering, the second term represents the increase due to radiation from the dust, and the third term represents the increase due to scattering of ambient light by the dust. The absorption coefficient \( a \) and scattering coefficient \( \sigma \) in Eq. [3] are expressed by Eqs. [4] and [5], respectively.

\[
a = X_a A N
\]

\[
\sigma = X_s A N
\]

where:
- \( X_a \): Absorption efficiency
- \( X_s \): Scattering efficiency
- \( A \): Cross-sectional area of dust
- \( N \): Number density of dust particles

The phase function \( \Phi \) is a function representing the directivity of scattering.

2.2 Theory of the IDC method

In the IDC method, two radiation thermometers are used, as shown in Fig. 1, with both measurements performed using two wavelengths. Radiation thermometer 1 measures the clinker temperature and radiation thermometer 2 measures the dust temperature in the kiln by facing a plate (nose–ring plate) (Fig. 2) attached to the outer circumference of the kiln exit end. The surface temperature of the nose–ring plate is as low as 1,000 °C, which is significantly lower than that of the clinker. Although it is necessary to install an additional measurement window for the radiation thermometer and to install a quartz plate to act as a blackbody for dust measurement in the DC method, the additional measurement window is not needed in the IDC method.

In the scattering properties of the pulverized and classified clinker, which forms the dust particles, the forward and backward scattering are much smaller than the direct light component when the measurement is carried out at 0.65 to 1.55 μm \(^{5} \). Therefore, the spectral raddiances \( L_1 \) and \( L_2 \) incident at radiation thermometers 1 and 2, which are found by solving the radiative transfer equations by adding the forward and backward scattering to the direct incident and by ignoring the third term on the right-hand side of Eq. [3], are given by Eqs. [6] and [7], respectively.

\[
\frac{dL'}{ds} = -(a + \sigma) L + a e_{dus} L_{dus} + \frac{\sigma}{4\pi} \int L' \Phi d\Omega
\]
Effect of wavelength on measurement accuracy

Here, the suffixes cli, dus, and n denote clinker, dust, and nose−ring plate, respectively, and \( \tau \) is a function of the cross-sectional area of the dust, number density of dust particles, and optical path length, and \( 1 − \tau \) represents the emissivity of the dust cloud. Since the dust emission terms \( (1 − \tau) L_{dus} \) are equal in Eqs. [6] and [7] because the measuring optical paths of the radiation thermometers 1 and 2 are almost the same, and since the nose−ring plate temperature is sufficiently lower than the clinker temperature, \( L_1 − L_2 \) is given by Eq. [8].

\[
L_1 − L_2 = \tau (\varepsilon_{cli} L_{cli} − \varepsilon_{dus} L_{dus}) = \tau \varepsilon_{cli} L_{cli} \tag{8}
\]

where the transmittance of dust can be approximated as equal between the two wavelengths since the optical properties of dust are almost the same at wavelengths in the range of 0.65 to 1.55\( \mu \)m at which measurement is carried out. It is also assumed that the emissivity of clinker is equal at wavelengths in the range of 0.65 to 1.55\( \mu \)m. Therefore, the influence of the transmittance of dust (transmission) and the emissivity of clinker can be removed by calculating Eq. [8] at two wavelengths and finding the ratio between them as given by Eq. [9].

\[
\frac{L_{1,\lambda_1} − L_{2,\lambda_1}}{L_{1,\lambda_2} − L_{2,\lambda_2}} = \frac{L_{cli,\lambda_1}}{L_{cli,\lambda_2}} \tag{9}
\]

where subscripts \( \lambda_1 \) and \( \lambda_2 \) indicate wavelengths. Since the right−hand side of Eq. [9] is the ratio between the spectral radiance of the clinker at two wavelengths, the clinker temperature \( T_{cli} \) can be obtained by applying the two−color temperature method (Eq. [2]). Furthermore, \( L_{cli} \) is obtained from \( T_{cli} \) by using Planck’s equation (Eq. [1]) and the transmittance \( \tau \) can be obtained by \( L_{cli} \) and Eq. [8].

\[
\tau = \frac{L_1 − L_2}{\varepsilon_{cli} L_{cli}} \tag{8'}
\]

\( L_{dus} \) is calculated by Eq. [6] by rewriting Eq. [6].

\[
L_{dus} = \frac{L_1 − \tau \varepsilon_{cli} L_{cli}}{(1 − \tau)} \tag{6'}
\]

The dust temperature is obtained by applying \( L_{dus} \) to Eq. [1].

2.3 Effect of wavelength on measurement accuracy

The accuracy of measurement by the IDC method can be improved by changing the measurement wavelength. Under the assumption that the temperature of the nose−ring plate is in the range of 800 to 1,000 °C and the error of the clinker temperature is estimated by the IDC method by using a model calculation based on Eqs. [6] and [7], the error is 10 to 45 °C for the wavelength combination of 0.90\( \mu \)m/1.55\( \mu \)m and 2 to 14 °C for the wavelength combination of 0.65\( \mu \)m/0.90\( \mu \)m (Fig. 3). Below wavelength ratios are expressed with “\( \mu \)m” omitted for simplicity. This is because the ratio between the spectral radiance of the
3. MEASUREMENT RESULTS IN AN ACTUAL EXISTING PRODUCTION KILN

3.1 Results of application of the IDC method

We conducted temperature measurement for 21 days at our plant (NSF type) and measured the clinker temperature and transmittance by using the IDC method (0.65/0.90), the IDC method (0.90/1.55), and the conventional two-color method (0.90/1.55). The results are shown in Fig. 4 and the average, maximum, and minimum value from the conventional two-color method (0.90/1.55) and IDC method (0.65/0.90) during the measurement period are shown in Table 2. The temperature difference between the IDC method (0.65/0.90) and the two-color method (0.90/1.55) during the measurement period was in the range of 29 to 229 °C, with an average of 93 °C, which indicates that IDC method is higher, and the transmittance was in the range of 0.02 to 0.33. As shown in Fig. 4, the transmittance was close to zero and the difference between measurement values was about 150 °C at around Jan 1st, while the transmittance was about 0.2 and the difference between the values was about 50 °C in the period of Jan 10 to Jan 14.

Fig. 5 shows the relationship between the temperature difference between the IDC method (0.65/0.90) and the two-color method (0.90/1.55) and the transmittance. It can be seen that the lower the transmittance (i.e. the higher the dust concentration), the larger the temperature difference between the IDC method (0.65/0.90) and the two-color method (0.90/1.55). This is because the temperature by the two-color method (0.90/1.55) is measured as being lower as the amount of dust, which decrease the measurement accuracy, increase, whereas the influence of dust is canceled by the IDC method (0.65/0.90).

In addition, the IDC method (0.65/0.90) was 28 °C lower than the IDC method (0.90/1.55). The newly introduced wavelength combination (0.65/0.90) thus eliminates the error where the measured temperature using the conventional wavelength combination (0.90/1.55) is higher than the true value as discussed in Section 2.3 “Influence of wavelength on measurement accuracy”.

3.2 Accuracy verification by spot measurement

To verify the measurement accuracy of the IDC method, the true value of the clinker temperature in

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**Table 1** Relationship between wavelength and spectral radiance

<table>
<thead>
<tr>
<th>Wavelength (μm)</th>
<th>Temperature (°C)</th>
<th>Ratio of spectral radiance</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>900</td>
<td>0.042</td>
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<td></td>
<td>1,450</td>
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<td></td>
<td>2,100</td>
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<td>2,850</td>
<td>0.028</td>
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<td></td>
<td>3,600</td>
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<td></td>
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<td>0.000</td>
</tr>
</tbody>
</table>

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Fig. 3 Relationship between nose–ring plate temperature and IDC method error

Fig. 4 Temperature of each method and transmittance

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Table 2  Results of measurements at our plant

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>Clinker temperature (°C)</th>
<th>Transmittance (°C)</th>
<th>Difference between IDC method (0.65/0.90) and two-color temperature (0.90/1.55)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Two-color temperature</td>
<td>IDC method</td>
<td></td>
</tr>
<tr>
<td>avg</td>
<td>1.365</td>
<td>1.458</td>
<td>0.16</td>
</tr>
<tr>
<td>max</td>
<td>1.423</td>
<td>1.588</td>
<td>0.33</td>
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<tr>
<td>min</td>
<td>1.282</td>
<td>1.394</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Fig. 5  Relationship between transmittance and difference between the IDC method (0.65/0.90) and two-color temperature (0.90/1.55)

Fig. 6  Radiation thermometer with optical fiber cable

Fig. 7  The schematic of spot measurement

Table 2 shows the results of measurements at our plant. The table lists the wavelength, clinker temperature, transmittance, and the difference between IDC method and two-color temperature.

The kiln was measured and compared with the temperature measured by the IDC method.

(1) Measurement method

To measure the true value of the clinker temperature in the kiln, measurements were carried out by installing the light collecting part of the radiation thermometer close to the clinker separated by about 50 cm in order to minimize the influence of dust. From the model calculation using Eq. [6], it was confirmed that temperature underestimation in the measurement due to dust can be limited to several degrees or less except when the transmittance is less than 0.1. An optical fiber was connected to the radiation thermometer and a lens was attached to the tip of the optical fiber (Fig. 6). These were then placed in a water-cooled probe to protect the optical fiber and lens, and were placed near the clinker (Fig. 7). Measurement by this method was limited to about 15 min because of heat and impact resistance.

It is debatable as to whether the temperature can be accurately measured by placing a radiation thermometer close to the clinker, and whether there is concern that the clinker temperature is measured as being high because the radiation from a high-temperature burner flame or similar reflected on the clinker surface is incident on the radiation thermometer.

The temperature of the clinker in the vicinity of the kiln exit end can be regarded as constant because it is just away from the burning zone at which the temperature is maximum and is beginning to be cooled slowly by secondary air. Therefore, the clinker is in a state of thermal equilibrium. With respect to heat transfer to and from the clinker, radiation heat transfer is dominant from the coal burning flame and the surrounding kiln inner wall, whereas convection heat transfer from secondary air and conductive heat transfer from refractories attached to the kiln inner wall are negligibly
small. Under these conditions, the average temperature of the environment around the clinker, including the flame and kiln inner wall, can be regarded as equal to the temperature of the clinker since the heat input to the clinker by radiation from the surroundings and the heat output by radiation from the clinker are equal. Therefore, the sum of the radiation from the clinker and the surrounding radiation reflected from the clinker surface can be regarded as equal to the blackbody radiation from the clinker, regardless of the clinker emissivity, indicating that it is possible to accurately measure the temperature of the clinker using a radiation thermometer sufficiently close to the clinker with an emissivity of 1 or by using the two-color method. In order for the above to hold, it is necessary for the reflection from the clinker surface to be diffuse reflection with no directivity. Since there is virtually no specular reflection from that surface, this assumption can be regarded as reasonable.

(2) Measurement results

Measurements were carried out at our two plants (SP type and NSP type). The measurement results for the relatively high transmittance of about 0.4 in the SP type are shown in Figs. 8 and 9, and those for the relatively low transmittance in the NSP type are shown in Figs. 10 and 11. Since the NSP type has a shorter retention time in the kiln than the SP type, it is thought that the clinker granulation action tends to be smaller.
and the dust concentration tends to be higher.

As shown in Figs. 8 and 9, the error between the IDC method (0.65/0.90) and the spot measurement value is in the range of about −15 to 25 °C, and the error between the conventional two-color method (0.90/1.55) and the spot measurement value is in the range of about −150 to −60 °C for the SP type. This shows that the error of the IDC method (0.65/0.90) is significantly smaller than the conventional two-color method (0.90/1.50). The temperature by the IDC method (0.90/1.55) can also be measured relatively accurately for the SP type. However, the temperature measured by the IDC method (0.90/1.55) is a little lower than the temperature measured by the IDC method (0.65/0.90), which is the reverse of the findings in Section 2.3 “Influence of wavelength on measurement accuracy”. While this could be due to the assumption of adding scattered light to direct light, the details are unknown.

As shown in Figs. 10 and 11, the error between the IDC method (0.65/0.90) and the spot measurement value is also in the range of about −15 to 25 °C, and the error between the conventional two-color method (0.90/1.55) and the spot measurement value is in the range of about −80 to −50 °C. This shows that the error of the IDC method (0.65/0.90) is significantly smaller than that of the conventional two-color method (0.90/1.50), the same as in the SP type. In addition, the IDC method (0.90/1.55) gives values higher by about 50 °C than the IDC method (0.65/0.90), and the measurement accuracy is greatly reduced. This confirms the effect of wavelength selection as discussed in Section 2.3 “Influence of wavelength on measurement accuracy”.

The spot measurement and the IDC method (0.65/0.90) give values in the range of about 1,350 to 1,450 °C, which is closer to the so-called burning zone temperature 1,450 °C than conventional two-color measurement values. The area in the vicinity of the exit of the kiln is called the cooling zone, and since the grain size of clinker is several tens of millimeters, the temperature is not expected to suddenly drop due to convective heat transfer by secondary air that is at 1,000 °C or more. Therefore, the values measured by the spot measurement value and the IDC method (0.65/0.90) are considered to be reasonable values.

3.3 Comparison of measurement results of DC method and improved DC method

Fig. 12 shows the results of simultaneous measurement by the DC method (0.65/0.90) introduced in Part 1 “Theory of the dust-canceling method and application to an existing kiln” and the IDC method (0.65/0.90). The temperature difference between the IDC method (0.65/0.90) and the DC method (0.65/0.90) is in the range of about −70 to 70 °C, and although they exhibit similar trends up until around 18:00, they do not coincide thereafter. The tendency of change in transmittance is also the same as the temperatures. On other dates during the measurement period, there were cases where there was difference and there was no difference between the DC method (0.65/0.90) and the IDC method (0.65/0.90). Since the measurement accuracy of the IDC method (0.65/0.90) was verified in 3.2 “Accuracy verification by spot measurement”, it was found that the measurement accuracy of the DC method is lower than that of the IDC method. As described in Part I, since the dust temperature and concentration on the measurement optical path of the radiation thermometer measuring a quartz plate are different from those of the radiation thermometer measuring clinker, the DC method (0.65/0.90) has measurement error. However, compared with the two-color method (0.90/1.55), the temperature was high enough, and the value was close to the IDC method (0.65/0.90), showing that the accuracy was greatly improved even over the DC method.

4. CONCLUSION

In this paper, in order to improve the energy saving of the clinker burning process, we devised an IDC
method, which can eliminate the dust influence including the distribution of dust inside the kiln and can measure the temperature of clinker at the edge of the kiln exit with high accuracy by using two radiation thermometers with almost identical optical paths. The following findings were obtained:

1) When measured by the IDC method at our plant for a long period (21 days), the lower the transmittance (the higher the dust concentration), the larger the difference between the DC method (0.65/0.90) and the conventional two-color temperature method (0.90/1.55). It was found that the influence of dust can be canceled by the IDC method.

2) A spot measurement method was established to measure the true value of the temperature of clinker inside the kiln. The measurement accuracy of the IDC method was verified by the spot measurement, and the error was in the range of about −15 to 25 °C. Since the measurement error of the conventionally used two-color method (0.90/1.55) was in the range of about −150 to −50 °C, the measurement accuracy was greatly improved compared with the conventional measurement method.

3) Model calculations were performed and showed that the measurement accuracy of the IDC method is higher with a measurement wavelength combination of 0.65/0.90 compared with the combination of 0.90/1.55. In the actual measurement, it was confirmed that the combination of 0.65/0.90 has the same or better measurement accuracy compared with 0.90/1.55.

4) It was confirmed that the IDC method gives better measurement accuracy compared with the DC method. However, it was found that even the DC method is significantly more accurate than the conventional two-color method.

In the future, we would like to create guidelines for kiln operation by analyzing the correlation between the values of the clinker temperature, the transmittance and the dust temperature obtained by the IDC method and the parameters of quality of clinker and operation data, and to contribute to energy conservation.

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REFERENCES: