Research on position calibration method in infrared scanning temperature measurement system of rotary kiln

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Abstract: Aiming at the large error in the equal-interval locating method, a precise position calibration method is proposed. The proposed method improves the location measurement accuracy by introducing some feature temperature points to divide the rotary kiln into several segments, then the equal-interval locating method was applied to each segment, ultimately, a position calibration data more closing to the actual situation was got. The feature temperature points can be selected from the temperature points of kiln tyres or the highest temperature point and so on. Taking the practical application into consideration, the best result is obtained, when four feature temperature points was introduced to divide the rotary kiln into five segments. The experiment result shows that compared with the equal-interval method, the accuracy of the proposed method has raised about 5.6 times when four feature temperature points is used.

Key words: Rotary kiln; Temperature measurement; Location calibration; Infrared

1. Introduction

Rotary kiln is the key equipment in the material burning process of cement production, whose performance directly affects the cement production and the main technical economic indicator [1-3]. Rotary kiln lining is constructed of firebreak brick, which may be seriously worn out or even fall off because of the temperature factor, chemical attack and mechanical wear, etc. Once the local firebreak brick falls off, it will pose a serious threat to the production and security [4-5]. The thickness of the rotary kiln lining can be detected through monitoring the surface temperature of the rotary kiln shell [6]. When somewhere on the rotary kiln appears abnormal high temperature, there may exist a hidden danger of "the red kiln" accident [7-9]. Therefore, it is necessary to accurately locate the fault position of rotary kiln, such as "the red kiln", to find out the fault position in time and to take remedial measures. The infrared scanning temperature measuring system of rotary kiln adopts equal-angle scanning mode, whose scanning angles between adjacent scanning points are equal. But the existing equal-interval locating method assumes that the distance between the adjacent scanning points is equal [10], while the distance between adjacent scanning points is not equal, so there is a large location error in equal-interval locating method, which could not meet the demand to achieve accurate position calibration. This paper

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proposes the precise position calibration method, which can improve the accuracy by introducing some feature temperature points to make a position correction on the equal-interval locating method. The test proves that precise position calibration method can control the positioning error in a smaller range, and it can meet the requirements of engineering applications.

2. Equal-angle scanning method of rotary kiln

2.1 Working principle of scanner

Fig. 1 equal-angle scanning diagram

The infrared scanning temperature measurement system of rotary kiln is made up of infrared temperature measurement scanner and temperature analysis software which is installed on computer [11]. The infrared scanner is consisting of infrared probe, motor and processor. The infrared scanner scans the whole surface of the rotary kiln through the rotation of infrared probe and rotary kiln. The infrared probe driven by motor scans the rotary kiln in horizontal direction and the rotary kiln rotates in vertical direction, as shown in Fig.1, therefore the scanner can detect the whole surface temperature data of rotary kiln. The infrared scanner collects the temperature data and sends it to the temperature analysis software to display whole temperature distribution of rotary kiln [12, 13].

2.2 The equal-interval locating method

The point i and the point $i+1$ represent two adjacent scanning points, as shown in Fig.2, the distance between the two adjacent scanning points is Δd ; the length of rotary kiln is L ; the total scanning point number is N .

Fig. 2 diagram of equal-interval positing method

The principle of the equal-interval locating method is that it assumes that the distance between each two adjacent scanning points is equal [14]. Δd can be

expressed as follow:

$$\Delta d = L / N \quad (1)$$

The position of scanning point i (the length from i to the head of rotary kiln) can be expressed as follow:

$$L_i = \sum_{n=0}^i \Delta d = \Delta d \times i = \frac{i \times L}{N} \quad (2)$$

3. The precise position calibration method

Fig. 3 diagram of precise position calibration

Rotary kiln has four tyres and the temperatures at the position of the tyres are very low, so the position of tyres is easy to distinguish. The precise position calibration method introduces some temperature point of tyres to make a correction on equal-interval method, and then get position data that are more close to the actual situation.

In this paper, we take four feature temperature points precise position calibration method for example, as shown in Fig.3, M_1 , M_2 , M_3 and M_4 represent the four feature temperature points; L_1, L_2, L_3 and L_4 are their real position. The position of the four feature points in equal-interval locating method are $L_{11}, L_{12}, L_{13}, L_{14}$; the scanning point number of feature points are N_1, N_2, N_3, N_4 ; the length of rotary kiln is L ; the total scanning point number is N , as shown in Fig.2, Δd in equal-interval locating method can be calculated as below:

$$\Delta d = L / N$$

The scanning point number of each feature temperature point can be express as follows:

$$\begin{cases} N_1 = L_1 / \Delta d = \frac{L_1 \times N}{L} \\ N_2 = L_2 / \Delta d = \frac{L_2 \times N}{L} \\ N_3 = L_3 / \Delta d = \frac{L_3 \times N}{L} \\ N_4 = L_4 / \Delta d = \frac{L_4 \times N}{L} \end{cases} \quad (3)$$

Then the position correction is made to improve the positioning accuracy, whose specific process is as follow:

Assuming the scanning interval Δi between each two feature temperature points is equal, Δi in precise calibration method can be expressed as follows:

$$\Delta i = \begin{cases} \frac{L_1 \times L}{L_{11} \times N} & (0 \leq i < N)_1 \\ \frac{L_2 - L_1}{N_2 - N_1} = \frac{(L_2 - L_1) \times L}{(L_{12} - L_{11}) \times N} & (N_1 \leq i < N_2) \\ \frac{L_3 - L_2}{N_3 - N_2} = \frac{(L_3 - L_2) \times L}{(L_{13} - L_{12}) \times N} & (N_2 \leq i < N_3) \\ \frac{L_4 - L_3}{N_4 - N_3} = \frac{(L_4 - L_3) \times L}{(L_{14} - L_{13}) \times N} & (N_3 \leq i < N_4) \\ \frac{L - L_4}{N - N_4} = \frac{(L - L_4) \times L}{(L - L_{14}) \times N} & (N_4 \leq i < N) \end{cases} \quad (4)$$

The position of scanning point m , which can be expressed as l_m , are calculated as follow:

$$l_m = \sum_{i=0}^m \Delta i \quad (0 \leq m < N) \quad (5)$$

Through Eq.(4) and Eq.(5) the position of each scanning point in precise calibration method can be calculated as follows:

$$l_m = \sum_{i=0}^m \Delta i = \begin{cases} \frac{L_1 \times L}{L_{11} \times N} \times m & (0 \leq i < N_1, 0 < m < N_1) \\ L_1 + \frac{(L_2 - L_1) \times L}{(L_{12} - L_{11}) \times N} \times (m - N_1) & (N_1 \leq i < N_2, N_1 < m < N_2) \\ L_2 + \frac{(L_3 - L_2) \times L}{(L_{13} - L_{12}) \times N} \times (m - N_2) & (N_2 \leq i < N_3, N_2 < m < N_3) \\ L_3 + \frac{(L_4 - L_3) \times L}{(L_{14} - L_{13}) \times N} \times (m - N_3) & (N_3 \leq i < N_4, N_3 < m < N_4) \\ L_4 + \frac{(L - L_4) \times L}{(L - L_{14}) \times N} \times (m - N_4) & (N_4 \leq i < N, N_4 < m < N) \end{cases} \quad (6)$$

4. Theoretic error analysis

Fig. 4 diagram of error analysis

In this paper, the length of rotary kiln is $60m$, that is $L = 60m$, the distance from scanner to the rotary kiln is $30m$, that is $H_1 = L/2 = 30m$, as shown in Fig.4, M_1 , M_2 , M_3 , M_4 represent the four feature temperature points on rotary kiln, H represent the head of rotary kiln, T represent the tail of rotary kiln, θ represent the unit scanning angle, ΔR_i represent the real scanning interval, Δ_i represents the scanning interval in precise position calibration method, Δ_d represents the scanning interval in equal-interval locating method. L can be calculated as follow:

$$L = \sum \Delta R_i = \sum \Delta d = 60 \quad (7)$$

The total scanning angle θ_t can be calculated as follow:

$$\theta_t = 2 \times \arctan(2 \times H_1 / L) = \pi / 2.$$

Since ΔR_i is symmetric to the midpoint of rotary kiln, we just need to discuss about error of the scanning points from the rotary kiln head to the midpoint. As ΔR_i is monotonous decrease function, so there must exist a scanning point k that can make the Eq.(8) work.

$$\Delta R_k = \Delta d = L / N \quad N \in \mathbb{N}^+ \quad (8)$$

Then the error of equal-interval locating method is analyzed as below:

Error of the scanning point i in equal-interval locating method E_i can be expressed as follow:

$$E_i = |LR_i - L_i| = \left| \sum_{n=0}^i (\Delta R_n - \Delta d) \right| \quad (9)$$

LR_i represents the real position of scanning point i ; L_i represents the position of scanning point i in equal-interval method. ΔR_i represents the real scanning interval.

When $0 < i < k$, it can be concluded that $\Delta R_i > \Delta d$, so the maximum error is E_k . Since the scanning angle is very small, so ΔR_k can be approximately calculated as follow:

$$\Delta R_k \approx H_1 \times (\tan(\frac{\pi}{4} - \theta \times k) - \tan(\frac{\pi}{4} - \theta \times (k+1))) \quad (10)$$

The unit scanning angle θ can be expressed as follow:

$$\theta = (\pi / 2) / 600 = \pi / 1200 \quad (11)$$

It can be calculated from the Eq. (8), Eq. (10) and Eq.(11) that the value of variable k is 115. The total angle β from k to the midpoint of rotary kiln can be calculated as below:

$$\beta = \frac{\pi}{4} - k \times \theta = 0.4843 \quad (12)$$

Through Eq.(2), the position of scanning point k in equal-interval can be calculated as follow:

$$L_k = \frac{115 \times L}{N} = 11.5 \quad (13)$$

The real position of scanning point k can be calculated approximately as follow:

$$L'_k \approx 30 - H_1 \tan(\frac{\pi}{4} - k \times \theta) = 14.2162 \quad (14)$$

So the maximum error E_{max} can be calculated as follow:

$$E_{max} = |L_k - L'_k| = 2.711 \quad (15)$$

Since ΔR_i is approximated as linear function, E_i can be approximated as linear function too. The minimum error in equal-interval method is 0, that is $E_{min} = 0$. The average error of the equal-interval method can be calculated as follow:

$$E_{ae} = \left| \frac{E_{max} + E_{min}}{2} \right| = 1.355 \quad (16)$$

Taking four feature temperature points for example, error of the precise position calibration method can be calculated as follow:

Four feature temperature points on rotary kiln are chosen, whose positions are listed as follow: $L_1 = 12m$, $L_2 = 24m$, $L_3 = 36m$, $L_4 = 48m$. According to temperature analysis and display software, we can get the position of the first feature temperature point in equal-interval locating method, that is $L_{11} = 9.3m$. Through Eq.(2), the number that the first feature point corresponds to is 93, that is $N_{m1} = 93$. Through Eq.(4), the scanning interval Δi between the rotary kiln head and the first feature point can be calculated as follow:

$$\Delta i = \frac{L_1 \times L}{L_{11} \times N} = 12 / 93 = 0.1290 \quad (17)$$

The calculation of the maximum error of the first segment is the same as the equal-interval locating method. Suppose the scanning point that the first segment maximum error corresponds to is K_{m1} . Through formula Eq.(8), Eq.(10) and Eq.(11), the value of K_{m1} is 41 can be calculated, that is $K_{m1} = 41$.

The maximum error of the first segment E_{Hm1max} can be calculated the same as E_{max} : $E_{Hm1max} = 0.6751$.

The calculations of the other segments' maximal error are the same as the calculation of HM_1 : $E_{m1m2max} = 0.4401$, $E_{m2m3max} = 0.3283$, $E_{m3m4max} = 0.4312$, $E_{m4Tmax} = 0.5561$ and the minimum error is $E_{min} = 0$. The average error of the precise calibration method can be calculated as follow:

$$E_{4e} = \left| \frac{E_{Hm1max} + E_{m1m2max} + E_{m2m3max} + E_{m3m4max} + E_{m4Tmax} + E_{min}}{5 \times 2} \right| = 0.24 \quad (18)$$

Comparing the average error E_{4e} and E_{ae} , we can find the accuracy of precise position calibration method using four temperature feature points has raised about 5.6 times.

$$E_{ae} / E_{4e} = 1.3581 / 0.2431 = 5.58 \approx 5.6 \quad (19)$$

The above-mentioned circumstance is $\theta_t = \frac{\pi}{2}$. When the scanning angle changes (is not 90 degrees), the accuracy also can be improved about 5.6 times, that is because the accuracy of precise position calibration method is related to the number of feature temperature points, instead of scanning angle.

5. Experiment result and analysis

The proposed method is tested by the infrared scanning temperature measurement system of rotary kiln which has already widely applied to cement production lines in China and the experimental data are all derived from the Southwest Cement Company Limited, where the length of rotary kiln is $60m$. The test results are shown in Fig.5; the horizontal axis represents the rotary kiln's length position and the vertical axis represents temperature. The blue curve depicts the relationship between temperature and position of the rotary kiln in precise position calibration method; the red curve correspond with the result of equal-interval locating method and the green curve correspond with the result of the real temperature and position value that collected with hand-held infrared thermometer at rotary kiln working site. The position of the maximum temperature on the equal-interval method curve is $3.0m$, but the real temperature data curve shows that the position of maximal temperature is $4.2m$, so we correct the maximal temperature from $3.0m$ to $4.2m$. The correction of other feature points are the same as the maximal temperature point, $17.1m$ is corrected to $19.4m$; $39.3m$ is corrected to $37.4m$ and $44.0m$ is corrected to $41.5m$. The experiment result is shown in Fig5. A comparison of the three curves indicates that the position information of precise calibration method quite agree with the real data of rotary kiln.

Fig. 5 comparison between equal-interval, precise calibration and real data

To further verify the accuracy of the method, this paper have used four points to make a correction, and some characteristic location data are selected from their result, which are listed in table.1.

Table 1 comparison of position calibration method

Real position(m)	Equal-interval(m)	Error of Equal-interval(m)	4 points calibration(m)	Error of 4 points calibration(m)
3.0	2.1	0.9	2.7	0.3
12.0	9.8	2.2	11.2	0.8
20.0	18.1	1.9	19.8	0.2
28.0	27.7	0.3	27.8	0.2
35.0	36.5	1.5	34.9	0.1
40.0	42.3	2.3	39.9	0.1
45.0	47.5	2.5	45.4	0.4
50.0	52.2	2.2	50.6	0.6
55.0	56.2	1.2	55.7	0.7
60.0	60.0	0.0	60.0	0.0

As shown in table.1, the first column represents the real position of scanning points; the second column represents the position of scanning points in equal-interval method; the third column represents the errors of each scanning point in equal-interval; the fourth column represents the position of scanning points in precise position calibration method, and the last column represents the errors of each scanning point in precise position calibration method. By compare the errors of each method in column 3 and column 5, the precise calibration method is more accurate than equal-interval method and the accuracy improved after removing the maximum and minimum value can be calculated as follow:

$$\frac{E_{ae}}{E_{4e}} = \frac{0.9}{0.3} = \frac{2+2}{0+2} = \frac{4.9+0.3}{+0.2+0.1} = \frac{1+5}{0.1+0.4} = \frac{2.2}{0.6} \approx \frac{1}{5} \quad (20)$$

Compare Eq.(19) and Eq.(20), we can find that the results of the experiment essentially correspond to the theoretical analysis.

6. Conclusion

In this paper, a precise position calibration method based on equal-interval locating method is proposed, which can accurately locate the temperature scanning point by making a correction on the equal-interval method. Experiment results and theoretical analysis shows that compared with the equal-interval position locating method, the proposed method not only raises the accuracy of precise position calibration about 5.6 times, but also provides a new idea for rotary kiln position calibration.

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