Thorium Ore Online System Design and Ore Detection Intensity Research

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Abstract. According to the radioactive characteristics of thorium ore and for the industrial production needs of thorium deposits in Baiyune, an online detection system for thorium ore concentrator with ten pulse counting was developed to realize real-time detection and ore beneficitation. The influence of the belt speed, ore shape, belt thickness, distance from the detector to the belt and other factors in the detection system on the \( \gamma \) energy exposure rate (intensity) in the incident NaI(Tl) crystal and the crystal detection efficiency are derived theoretically. Finally, it is made about the error evaluation of the online system in industrial production.

Keywords: ten-channel pulse counting; online detection system; theoretical formula derivation; error evaluation

1. Introduction
The thorium grade of most thorium deposits in China is low. In actual thorium ore beneficitation, thorium ore with low thorium content in these metal ores cannot be accurately separated. According to the method of nuclear analysis technology, the thorium ore screening machine is used to detect the gamma rays emitted by the thorium ore to sort out high-grade thorium ore, which provides technical support for the sorting of thorium-containing ore [1].

2. Design of Online Detection System for Thorium Ore

2.1. System Equipment Plan

![Figure 1. The plan view of thorium ore online monitoring device.](image)
The ore is distributed on the belt of the main engine with a certain gap, and passes through the radioactive detection area in turn. The detection part of the concentrator consists of ten probes under the belt of the main machine. The ore sequentially passes through ten evenly placed probes under the belt, and the probes send the collected signals to the subsequent circuit in the main box for processing. After processing the data collected in the radioactive detection area, the radioactivity of the ore can be monitored in real time. When the radioactivity is lower than the lower threshold, it is judged as tailings waste. When it is higher than the upper threshold, it is judged as concentrate [2].

As shown in Figure 1, the detector is evenly placed. The radius of NaI(Tl) crystal is R1. The height of crystal is D. The crystal spacing is L. The belt thickness is S/2. The distance between the detector crystal and the top of the belt is H. The velocity is v, the length is S1. The time of ore movement is t (t ∈ (0, S1/v)), and the radius of the spherical thorium ore sample is r1.

2.2. System Parameter Setting in Industrial Production

The size of the crystal used in industrial production is 50 mm × 50 mm × 20 mm. According to the amount of ore conveyed, the bandwidth of the conveyor belt is usually 500-1400 mm, the speed of the conveyor belt is 0.8-6.5 m/s, the feed size is 50-500 mm, and the drum diameter is 500-1600 mm.

The system parameters used in this article in the industry are shown in Table 1 [3, 4]:

| Parameter index | Parameter |
|-----------------|-----------|
| Transmission method | Horizontal transfer |
| Interface connection method | Sulfur (plastic) |
| Working temperature/°C | -15 ~ +40 |
| Roll diameter/mm | 500 |
| Band width/mm | 100 |
| Length S1/m | 1 |
| Crystal interval L/mm | 50 |
| Speed v/(m/s) | 1 |
| Feeding granularity r1/mm | 10 - 75 |
| Belt thickness S/mm | 66 |
| Band width/mm | 586 |
| Length S1/m | 25 |

3. Derivation of Theoretical Formula for Crystal Incident Energy Intensity

The deposited gamma ray energy in the crystal directly affects the measurement of the thorium ore count rate of the system. Therefore, it is necessary to calculate the influence of each parameter on the intensity of gamma rays.

3.1. Incident Energy Intensity

We establish a spherical coordinate system with the point of the ore sphere as the origin. Any small-volume element in the sphere is \( dV = r^2 \sin \theta dr d\theta d\phi \) (1).

The mass of the radionuclide is \( dm = q \rho dl \), and the exposure rate at the center of the sphere is \( dI \), as shown in formula (2).

\[
dI = \frac{Kd_m}{r^2} e^{-(u(r-r_0)-u_0(r_1-r_0)-u_1)}
\]

K is the gamma constant. The linear attenuation coefficients of radiator, air and belt to gamma rays are \( u, u_0 \) and \( u_1 \) respectively. The penetration distances are \( r, r_0 \) and \( r_2 \) respectively. The penetrating
distances are \( r, r_0 \) and \( r_2 \). The radionuclide content of thorium ore is \( q \). The density is \( \rho \).

The geometric relationship between ore and crystal is shown in figure 2:

Figure 2. Schematic diagram of the geometric relationship between thorium ore and crystal.

There are \( i \) instruments from left to right (\( 1 \leq i \leq 10 \)). And the relationship between exposure rate and time is obtained by integration, as shown in formula (3).

\[
d_{hi} = Kq\rho \int_0^{2\pi} d\theta' \int_0^R dR \int_0^{2\pi} d\varphi \int_0^{\arcsin \left( \frac{R}{r_i} \right)} \sin \theta d\theta \int_{X_{hi}}^\infty e^{-\mu (r-r_0)+(h_0-n_i)+(n_1-n_i)} d_r
\]

Let \( n_i = S_i - (11-2i)L - (24-4i)R_i \), the physical meaning of \( n_i \) is the distance between the left edge of the belt and the left edge of the \( i \)-th crystal divided by 2. The distance from any point \( p \) in the cylindrical crystal to the center point of the sphere is \( X_i \), as shown in formula (4).

\[
X_i = \sqrt{\left( R \sin \theta' \right)^2 + \left( R - |R \cos \theta'| + \frac{n_i}{2} - vr \right)^2 + \left( D - h + H + r_i \right)^2 - r_i^2}
\]

the upper and lower limit of points are shown in formula (5) and formula(6).

\[
X_{hi} = X_i \cos \theta + \sqrt{r_i^2 - X_i^2 \sin^2 \theta}
\]

\[
X_{hl} = X_i \cos \theta - \sqrt{r_i^2 - X_i^2 \sin^2 \theta}
\]

The distance \( r_{hi} \) of gamma rays through the belt and the distance \( r_{hl} \) through the air are shown in formula (7) and formula (8).

\[
r_{hi} = X_{hi} - r_i
\]

\[
r_{hl} = \begin{cases} 
\frac{S}{\cos (\arccos \frac{X_i}{D-h+H+r} + \theta)} & \theta \in (0, \pi) \\
\frac{S}{\cos (\arccos \frac{X_i}{D-h+H+r} - \theta)} & \theta \in (\pi, 2\pi)
\end{cases}
\]

The total exposure rate \( I \) is shown in formula (9).

\[
I = \int_0^\infty \sum_{i=1}^{10} d_{hi} d_t
\]

It is concluded that the gamma-ray exposure rate \( I \) is inversely related to the velocity \( v \), the belt
thickness $S$, and the distance $H$ from the detector to the crystal, and is positively related to the radius $r$.

### 3.2. Crystal Detection Efficiency

Since the crystal is far away from the thorium ore, the crystal detection efficiency of the thorium ore is a point source [6]. The detection efficiency is shown in formula (10).

$$
\varepsilon_m = \int_\Omega \frac{1}{4\pi} e^{\text{u}_0 \cdot \text{u}_1} \left(1 - e^{\text{u}_2 \cdot \text{u}_3}\right) \sin \alpha d\alpha d\phi
$$

(10)

$\Omega$ is the solid angle $\text{u}_2$, $\text{u}_1$ and $\text{u}_0$ are the linear absorption coefficients of NaI(Tl). Belt and air for gamma rays. $y_0$, $y_1$ and $y_2$ are the penetration distances of gamma rays through air, belt and crystal respectively.

Schematic diagram of the geometric relationship between ore and crystal is shown in figure 3.

![Schematic diagram](image)

**Figure 3.** Schematic diagram of geometric relationship between ore and crystal.

When $t \in (\frac{n_1}{2v}, \frac{n_1 + 2R_1}{v})$, the point source is within the crystal radius, as shown in figure 3(a). The angle $\alpha_m$ and distance $S_{C1C4}$ are shown in formula (11) and formula (12).

$$
S_{C1C4} = \sqrt{R_1 - S_{OC}, \sin^2 \theta - S_{OC}, \cos \phi}
$$

(11)

$$
\alpha_m = \begin{cases}
\arctan \frac{S_{C1C4}}{D + H + R_1}, m = 1 \\
\arctan \frac{S_{C1C4}}{R_1}, m = 2
\end{cases}
$$

(12)

Among them, $S_{C1C4}$ is the distance from C1 to C4, and $S_{OC} = \sqrt{\left(\frac{vt}{2} + \frac{R_1}{2}\right)^2}$ is the distance from O to C1. $y_0, y_1, y_2$ are shown in formula (13), formula (14) and formula (15).

$$
y_0 = \frac{D + R_1 - S}{\cos \alpha}
$$

(13)

$$
y_1 = \frac{S}{\cos \alpha}
$$

(14)

$$
y_2 = \begin{cases}
\frac{D}{\cos \alpha}, \alpha \in (0, \alpha_1) \\
\frac{S_{OC} - \frac{R_1}{\cos \alpha}, \alpha \in (\alpha_1, \alpha_2)}
\end{cases}
$$

(15)

When $t \in (0, \frac{n_1}{2v})$, $t \in (\frac{n_1 + 2R_1}{v}, \frac{n_1}{v})$, the point source is outside the radius, as shown in figure 3(b). $S_{B6O}$, $S_{B2B3}$, $S_{B2B5}$ are shown in formula (16), formula (17), formula (18) and formula (19).

$$
S_{B6O} = \left|y_1 - vt + R_1\right|
$$

(16)

$$
S_{B2B3} = S_{B6O} \cos \phi - \sqrt{R_1^2 - S_{B6O}^2 \sin^2 \phi}
$$

(17)

$$
S_{B2B5} = S_{B6O} \cos \phi + \sqrt{R_1^2 - S_{B6O}^2 \sin^2 \phi}
$$

(18)
Among them, $S_{RBB3}, S_{RBB5}, S_{BBBS}$ are the distances from $B_2$ to $B_3$, $B_2$ to $B_5$, and $B_1$ to $B_3$.

When $a_2 < a_1$, namely $t \in \left(0, \frac{n - 2S_{RBB3} \cos \phi}{2v}\right) \cap \left(\frac{n + 2S_{RBB3} \cos \phi + 4R}{2v}, \frac{n + 2S_{RBB5} \cos \phi + 4R}{2v}\right)$, $y_0, y_1, y_2$ are shown in formula (20), formula (21) and formula (22).

\[
y_0 = \frac{y_0 - \frac{S_{RBB3}}{\sin \alpha} \frac{S}{\cos \alpha}, \alpha \in (a_i, a_i)}{a + H - S, \alpha \in (a_i, a_i)} \tag{20}
\]

\[
y_1 = \frac{y_1 - \frac{S_{RBB3}}{\sin \alpha} \frac{S}{\cos \alpha}, \alpha \in (a_i, a_i)}{a + H - S, \alpha \in (a_i, a_i)} \tag{21}
\]

\[
y_2 = \left\{ \begin{array}{l}
\frac{D + H + R}{\cos \alpha} - \frac{S_{RBB2}}{\sin \alpha}, \alpha \in (a_i, a_i) \\
\frac{S_{RBB2}}{\sin \alpha} - \frac{\frac{n + H}{\cos \alpha}, \alpha \in (a_i, a_i)}{\cos \alpha}
\end{array} \right. \tag{22}
\]

When $a_2 > a_1$, namely $t \in \left(\frac{n - 2S_{RBB3} \cos \phi}{2v}, \frac{n + 4R}{2v}\right) \cap \left(\frac{n + 2S_{RBB5} \cos \phi + 4R}{2v}, \frac{n + 2S_{RBB3} \cos \phi + 4R}{2v}\right)$, $y_0, y_1, y_2$ are shown in formula (23), formula (24) and formula (25).

\[
y_1 = \frac{y_1 - \frac{S_{RBB3}}{\sin \alpha} \frac{S}{\cos \alpha}, \alpha \in (a_i, a_i)}{a + H - S, \alpha \in (a_i, a_i)} \tag{23}
\]

\[
y_2 = \left\{ \begin{array}{l}
\frac{y_2 - \frac{S_{RBB3}}{\sin \alpha} \frac{S}{\cos \alpha}, \alpha \in (a_i, a_i)}{a + H - S, \alpha \in (a_i, a_i)} \\
\frac{D + H + R}{\cos \alpha} - \frac{S_{RBB2}}{\sin \alpha}, \alpha \in (a_i, a_i) \\
\frac{D}{\cos \alpha} - \frac{S_{RBB2}}{\sin \alpha}, \alpha \in (a_i, a_i)
\end{array} \right. \tag{24}
\]

\[
y_2 = \left\{ \begin{array}{l}
\frac{y_2 - \frac{S_{RBB3}}{\sin \alpha} \frac{S}{\cos \alpha}, \alpha \in (a_i, a_i)}{a + H - S, \alpha \in (a_i, a_i)} \\
\frac{D}{\cos \alpha} - \frac{S_{RBB2}}{\sin \alpha}, \alpha \in (a_i, a_i)
\end{array} \right. \tag{25}
\]

It is concluded that the detection efficiency of the crystal depends on the belt thickness $S$, the source distance, the size of the crystal and the size of the ray energy ($u_0, u_1, u_2$ are related to $E$).

4. Errors of the System in Industrial Production

The industrial error of the system mainly comes from the error caused by the different ore block shape and the error caused by the different starting position.

4.1. Errors Caused by Different Lumps

The ore size is set to $\Phi 10$cm, but in actual production, the ore will vary in size. According to the actual production situation, the size of the ore is in the range of $\Phi 5-15$cm. When the elements of thorium ore are evenly distributed and the content and density are constant, the activity of thorium ore is linearly related to the volume of thorium ore.
The activity ratio of ore with different lumpness relative to Φ10cm ore is shown in the table.

Table 2. Relative to 10cm diameter ore activity ratio table.

| Lumpiness/cm | Φ5  | Φ7.5 | Φ10 | Φ12.5 | Φ15  |
|--------------|-----|------|-----|-------|------|
| ratio        | 0.125 | 0.422 | 1.000 | 1.953 | 3.375 |

It can be seen from table 2 that the size of the ore has a great influence on the counting, so we should try our best to ensure that the volume of the ore screened in the same batch is basically the same, and select the ore with a relatively high count from it to ensure the accuracy of the beneficiation.

4.2. Errors Caused by Different Starting Positions
In industrial production due to batch operation, according to formula (7), the time that the ore runs on the belt is different, and the energy deposited in the energy crystal of the crystal decreases.

We set the conveyor belt speed to 1m/s, as shown in Figure 1. If the ore is at point A, the total measurement time is 1s, and the error is 0. When the ore is at point B, the total measurement time is t₁. The error is \((1-I_t/I_t)\); when the ore is at point C, the total measurement time is t₂, and the error is \((1-I_t/I_t)\). In industrial production, since the time error caused by the different starting measurement positions does not exceed 5%, the impact on the online detection of ore can be ignored.

5. Conclusion
In this paper, an on-line detection system for thorium ore concentrator with 10-channel pulse counting is developed for industrial production requirements, and a theoretical formula is made for the influence of factors in the detection system on the source of thorium ore and the efficiency of crystal when the ore is used as a point source. Derive. It can be concluded that the gamma-ray exposure rate I is inversely related to the velocity v, the belt thickness S, and the distance H from the detector to the crystal, and is positively related to the radius r. The detection efficiency of the crystal depends on the belt thickness S, the source distance, the size of the crystal (r, D) and the size of the ray energy. In industrial applications, in order to reduce the error, the size of the ore should be basically the same as the starting position and the distance between the ore should be large enough.

Acknowledgments
The authors thank to The College of Nuclear Technology and Automation Engineering, Chengdu University of Technology, Contract 2017YFC0602105 for the financial support of this study.

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