Prediction method of coal slagging property in layer-fired boiler

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Abstract. In this article, different coal samples are selected and their physicochemical properties are analyzed. Study and comprehensively analyze various factors affecting slagging. Prediction of coal slagging properties using 12 influencing factors, include: softening temperature, the difference between deformation temperature and flow temperature, characteristic of char residue, sodium oxide content, silicon ratio, silica-alumina ratio, iron-calcium ratio, acid-base oxide ratio, sulfur slagging index, contamination index, chlorine content, inorganic mineral content. The fuzzy clustering analysis method was used to classify and quantify all the influencing factors, and the coal slagging prediction method of layer fired boiler was proposed and verified by application.

1. Introduction
The slagging, ashing and ash accumulation of the layer fired boiler is a comprehensive change process of coal combustion and pyrolysis and melting of minerals in coal. The type of grate, the atmosphere in the boiler, the physical and chemical properties of the coal will cause mutual coupling. It is also directly related to the design and operating conditions of the overall boiler. Therefore, the problem of slagging in a layer-fired boiler is a practical problem of cross-disciplinary and infiltration. These factors have seriously affected the safety and economic and environmental protection of the boiler. The discriminative indicators for predicting slagging, such as slag characteristics, ash fusibility and other physical and chemical indicators, failed to comprehensively summarize all the factors, leading to slagging in the actual operation process. At present, the fuel of boiler equipment is usually not a single type of coal, which deepen the difficulty in judging the performance of slagging. Therefore, combined with internal factors and external factors can make comprehensive prediction of coal slag combustion slagging more reasonable. The multi-factor weights are used and eventually classified as a single indicator to reflect the degree of coal slagging. In order to reduce the deviation caused by the change of threshold value, the fuzzy judgment method is introduced into the discriminating range of the influencing factors, so that the final discriminant index is more realistic and more convincing, making the prediction result more objective.

2. Study on the physicochemical properties of coal samples
The 13 kinds of coal samples in the operation of the layer-fired boiler were selected, the industrial analysis of the samples was analyzed, the elemental analysis was carried out, and the thermogravimetric analyzer was used to study the weight loss process of the coal pyrolysis, the heat
absorption and desorption process, and the weight loss with temperature. The composition and content of minerals in coal were analyzed by X-ray fluorescence spectrometer and X-ray diffractometer.

The weight loss of the coal sample is analyzed by thermogravimetric analysis, and the coal does not burn in an inert atmosphere. The main weight loss is derived from the precipitation, pyrolysis and phase transformation of the volatile matter. In the interval of 300°C to 600°C, the weight loss is obvious, mainly the release of volatiles in coal. At 500°C, the chloride begins to volatilize, accompanied by pyrolysis and phase transformation. Carbonate pyrolysis at 600-1000°C, forming free alkali metal compound, while releasing CO₂. In the range of 900°C to 1200°C, alkali metal compounds volatilized, there is about 2% weight loss, through the curve can be found. At 1000°C, the residual part of the basic and coal quality analysis of the volatilization the content of the fraction is close.

Coal contains clay minerals, carbide minerals, carbonate minerals, sulfate minerals, chloride minerals and silicate minerals. These minerals will undergo pyrolysis and eutectic combustion in the combustion process of a layer-fired boiler. Quantitative analysis of minerals determines the mineral composition of the coal sample. Through data and theory, the eutectic of acidic oxides and basic oxides, SiO₂ and Al₂O₃, the melting point of Fe oxides in different atmospheres, and the low-melting alkali metal compounds such as Na₂O and K₂O are the effects of minerals on the ash deposition of coal ash. The key to the factors.

![Figure 1. Weight loss in an inert atmosphere.](image1)

![Figure 2. Relationship between silicon ratio and deformation temperature](image2)

![Figure 3. Relationship between acid-base ratio and deformation temperature](image3)

Through different indicators to explore the impact on the slagging between them, it is found that the index prediction of each coal sample indicates that the coal sample is severely slagging, and the
other indicators predict that the coal sample is slightly slagging or not slag, they are contradictory.

| Sample | ST | ΔT | CB | Na | G | Si/Al | Fe/Ca | B/A | S | Rf | Cl | MM |
|--------|----|----|----|----|----|-------|-------|-----|---|----|----|----|
| AH     | M  | M  | L  | N  | M  | S     | L     | M   | L | S  | M  | L  |
| BH     | M  | L  | L  | N  | M  | M     | M     | M   | S | S  | S  | L  |
| CH     | S  | S  | L  | N  | S  | M     | M     | S   | N | L  | M  | L  |
| DH     | M  | S  | L  | N  | L  | S     | M     | L   | S | S  | S  | L  |
| EH     | L  | N  | L  | N  | M  | S     | L     | M   | M | S  | M  | L  |
| FH     | N  | N  | M  | N  | M  | L     | M     | L   | S | S  | M  | M  |
| GH     | S  | M  | L  | N  | S  | S     | M     | S   | N | S  | S  | L  |
| HH     | L  | S  | L  | N  | M  | M     | L     | L   | S | S  | L  | L  |
| IH     | M  | S  | L  | N  | M  | S     | L     | M   | S | S  | S  | L  |
| DY1    | S  | M  | L  | M  | M  | S     | M     | M   | S | L  | S  | L  |
| DY2    | L  | N  | L  | N  | L  | M     | M     | L   | S | S  | L  | S  |
| DYH    | S  | S  | L  | N  | S  | S     | M     | S   | M | L  | M  | L  |
| TH1    | S  | S  | L  | N  | S  | S     | M     | S   | L | L  | M  | M  |

(S= severe slagging, M= medium slagging, L= light slagging, N= non-slagging)

3. Establish fuzzy clustering analysis

The limit value of the traditional discriminant index is a step function. When the calculated value of the index is near the critical value, a small amount of change will affect the level of the slag level. In order to reduce the deviation caused by the change of threshold value, the fuzzy judgment method is introduced into the discriminating range of the influencing factors, so that the final discriminant index is more realistic and more convincing, making the prediction result more objective. Using fuzzy clustering analysis method, the slagging factor becomes a mathematical quantitative form, and then the relationship between these factors is judged. Through the membership function of each factor, the evaluation limit is judged, and finally an overall evaluation value is obtained.

3.1 Establish fuzzy factor sets and evaluation levels

Combining the influencing factors of the slagging evaluation object $x = \{x_1, x_2, \cdots, x_p\}$, $j = 1, 2, \cdots, p$

Using the physical and chemical experimental data, 12 discriminating factors were selected as follows:

1) Softening temperature of ash meltability (ST): a comprehensive indicator for measuring grate and heating surface slagging;
2) The difference between deformation temperature and flow temperature (ΔT): measuring the ability of ash from melting to cooling;
3) Characteristic of char residue (CB): measure the shape of coal char after staying at 900°C;
4) Sodium oxide content (Na): measure the Na$_2$O content that is most prone to ash formation; equivalent $Na_2O = (Na_2O + 0.659K_2O) \times 100$
5) Silicon ratio (G): the components in the denominator are mostly fluxes, and the higher the silicon ratio means less adhesion. $G = SiO_2 / (\text{equivalent Fe}_2O_3 + SiO_2 + MgO + CaO)$ equivalent $Fe_2O_3 = Fe_2O_3 + 1.11$
6) Silica-alumina ratio (Si/Al): SiO$_2$ and Al$_2$O$_3$ are the main acidic substances in coal ash, and this ratio can judge the melting point of the acidic oxide eutectic;
7) Iron-calcium ratio (Fe/Ca): judging the slagging factors of bituminous coal ash;
8) Acid-basic oxide ratio (B/A): judging according to the tendency of the melting point of the acidic oxide and the basic oxide; $B / A = (Fe_2O_3 + CaO + MgO + K_2O + Na_2O_2)$
9) Sulfur slagging index \((S)\): considering that pyrite in coal ash is a flux, it is easy to reduce the ash melting point; \(R_s = A / B \times S_d\).

10) Contamination index \((R_f)\): considering the degree of coal bonding; \(R_f = A / B \times (Na_2O)

\[ Na_2O = (Na_2O + K_2O) \]

11) Chlorine content \((Cl)\): factors in determining fusible alkali metal oxides;

12) Inorganic mineral content \((MM)\): as a factor in the quality of slag in coal;

\[ MM_x = 1.129A_2 + 0.35S_d - 0.2 \]

The set \(V\) of the various evaluation levels divided by the judged object according to the discriminant limit; the predictive index is divided into non-slagging, light slagging, medium slagging and severe slagging according to the foregoing. When calculating the dispersion standard value (the center value of the indicator divided by the maximum value of each indicator), the center value of the range is required and determined. The discriminant limits and center values are summarized, as shown in Table 2:

| Index  | non-slagging (ST) | light slagging (AT) | medium slagging (CB) | severe slagging (Na) |
|--------|-------------------|---------------------|----------------------|----------------------|
| central value | 1500.00 | 1445.00 | 1325.00 | 1260.00 |
| Discriminant limit | > 1500 | 1390-1500 | 1260-1390 | < 1260°C |
| central value | 200 | 175 | 125 | 75 |
| Discriminant limit | > 200 | 150-200 | 100-150 | < 100 |
| central value | 1.00 | 2.00 | 4.00 | 7.00 |
| Discriminant limit | 1, 2 | 2, 3 | 4, 5 | 6, 7 |
| central value | 0.30 | 0.38 | 0.53 | 0.67 |
| Discriminant limit | < 0.3 | 0.3-0.45 | 0.45-0.6 | > 0.6 |
| central value | 78.80 | 75.40 | 69.05 | 63.15 |
| Discriminant limit | > 78.8 | 78.8-72 | 72-66.1 | < 66.1 |
| central value | 2.00 | 1.94 | 2.26 | 3.04 |
| Discriminant limit | < 1.87 | 2-1.87 | 2.65-1.87 | > 2.65 |
| central value | 0.30 | 3.00 | 1.35 | 1.35 |
| Discriminant limit | < 0.3 | 3 | 0.3-3 |
| \(Si/Al\) | central value | 0.15 | 0.15 | 0.31 | 0.49 |
| Discriminant limit | < 0.206 | 0.1-0.206 | 0.206-0.4 | > 0.4 |
| central value | 0.50 | 1.30 | 2.30 | 2.90 |
| Discriminant limit | < 0.6 | 0.6-2.0 | 2.0-2.6 | 2.60 |
| central value | 0.13 | 0.35 | 0.75 | 1.25 |
| Discriminant limit | < 0.2 | 0.2-0.5 | 0.5-1 | > 1 |
| central value | 0.10 | 0.25 | 0.40 | 0.60 |
| Discriminant limit | < 0.2 | 0.2-0.3 | 0.3-0.5 | > 0.5 |
| central value | 2.5 | 7.25 | 15 | 25 |
| \(Fe/Ca\) | Discriminant limit | 0-5 | 5-10 | 10.01-20 | > 20 |

3.2 Determine membership functions and specify clustering rights

Determine the membership function: list the triangle membership function for the factors with the evaluation limit, and divide the slagging degree into four grades. Take the softening temperature as an example. The expression is as follows:

\[ f_{11}(t) = \begin{cases} 
1, & t > 1500 \\
\frac{t-1445}{55}, & 1000 < t \leq 1500 \\
0, & t < 1445 
\end{cases} \]  

(3.1)
Light slagging: \( f_{j12}(t) = \begin{cases} 
0, & t > 1500 \\
\frac{t-1445}{60}, & 1500 < t < 1445 \\
\frac{t-1385}{60}, & 1385 < t < 1445 \\
1, & t = 1445 \\
0, & 1445 < t, \ t > 1195 \\
\end{cases} \) (3.2)

Medium slagging: \( f_{j13}(t) = \begin{cases} 
0, & t > 1325 \\
\frac{t-1325}{130}, & 1325 < t < 1445 \\
\frac{t-1195}{130}, & 1195 < t < 1325 \\
1, & t = 1325 \\
0, & 1325 < t \\
\end{cases} \) (3.3)

Severe slagging: \( f_{j13}(t) = \begin{cases} 
0, & t > 1325 \\
\frac{t-1325}{130}, & 1195 < t < 1325 \\
1, & t < 1195 \\
\end{cases} \) (3.4)

Calculating clustering coefficients \( \delta_{jk} \):
\[
\delta_{jk} = \sum_{j=1}^{p} f_{jk}(X_{ij}) \eta_{jk} \quad \text{In formula}, \quad i=1,2\ldots n; \quad k=1,2\ldots m \\
(\ n: \ \text{number of samples}, \ m: \ \text{number of grades})
\] (3.5)

3.3 Determine the dispersion standard value and cluster weight value
According to the discrimination of classification boundaries and the judgment of single results, in order to eliminate the difference in the magnitude of different indicators, the data of the grading standards are processed, and the central value of each indicator is divided by the maximum value of each indicator.
\[
M_{j} = i_{max}(x_{ij}) \ldots \ldots i=1,2\ldots 13 \\
\lambda_{ij} = \frac{x_{ij}}{M_{j}} \quad \ldots \ldots j=1,2,3,4
\] (3.6) (3.7)

According to different evaluation levels, determine the relative weight of each level of the corresponding level
\[
\eta_{jk} = \lambda_{jk} / \sum_{j=1}^{p} \lambda_{jk} \ldots \ldots \text{In formula}, \quad \lambda_{jk} \ \text{Standard value}, \quad j=1,2\ldots p \ \text{Number of factors}, \quad k=1,2\ldots m \ \text{Number of grades}
\] (3.8)

4. Result analysis
Normalize the four evaluation index values of each clustering coefficient (the sum of the clustering coefficients of the four evaluation indicators is 1), and determine the classification according to the maximum principle (if there are two numerical differences less than 0.15, take the more serious prediction index), finally get Table 3.

| sample | non-slacking | light slagging | medium slagging | severe slagging | forecast result |
|--------|--------------|----------------|-----------------|-----------------|-----------------|
| AH     | 0.12         | 0.38           | 0.35            | 0.14            | medium slagging |
| BH     | 0.20         | 0.24           | 0.34            | 0.20            | medium slagging |
| CH     | 0.21         | 0.05           | 0.21            | 0.53            | severe slagging |
| DH     | 0.43         | 0.04           | 0.19            | 0.35            | severe slagging |
| EH     | 0.43         | 0.24           | 0.17            | 0.16            | non-slacking    |
| FH     | 0.43         | 0.22           | 0.28            | 0.07            | non-slacking    |
|   | GH  | HH  | IH  | DY1 | DY2 | DYH | TH1    |
|---|-----|-----|-----|-----|-----|-----|--------|
|   | 0.46| 0.44| 0.14| 0.00| 0.47| 0.16| 0.18   |
|   | 0.07| 0.19| 0.49| 0.10| 0.09| 0.08| 0.13   |
|   | 0.17| 0.12| 0.14| 0.49| 0.49| 0.11| 0.00   |
|   | 0.31| 0.25| 0.23| 0.41| 0.26| 0.65| 0.69   |
|   |     |     |     |     |     |     |        |
|   |     |     |     |     |     |     |        |
|   |     |     |     |     |     |     |        |
|   |     |     |     |     |     |     |        |

### 5. Conclusion

In this paper, fuzzy clustering analysis method is established to predict the slagging property of coal-fired boilers. The prediction index is divided into non-slaking, slight slagging, medium slagging and severe slagging. The determination of the boundary and the determination of the membership function relationship are finally predicted. After this method, an overall evaluation value is obtained, which makes the prediction result more accurate and objective. The discriminating factors of coal-fired slagging of layered boilers are difficult to classify and difficult to quantify into clear and simple mathematical quantitative indicators.

In practical engineering applications, using the single-index experimental data available at the site, this fuzzy clustering analysis method is used to provide a new way to predict coal slagging performance of layer-burning boilers. There are still many shortcomings in the research of coal slag after combustion. If combined with the analysis of coal slag after combustion at different temperatures, the choice of predictive factors will be more objective and accurate.

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