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Study on Optimization of Denitration Technology Based on Gray-fuzzy Combined Comprehensive Evaluation Model

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Abstract
This paper establishes a combined evaluation model on the basis of Fuzzy Comprehensive Evaluation and Gray Relational Analysis. Through Fuzzy Comprehensive Evaluation it achieves the reasonable conversion from qualitative to quantitative and through Gray Relational Analysis it sets the weight of each index, which making sure that the evaluation model is scientific and rational. Then, with the combined evaluation model, it evaluates the performance of SCR, SNCR, SNCR/SCR which are relatively more mature flue gas denitrification technology. The evaluation result verifies the effectiveness and practicality of the model. And meanwhile, it could be a valuable reference for the promotion of the denitration devices and the formulation of the denitration price. At last, it provides a powerful guarantee to the power engineering construction.

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Keywords: Fuzzy Comprehensive Evaluation; Gray Relational Analysis; denitration technology; denitration price

1. Introduction

With great efforts of environmental protection in China, denitration device has been installed in more and more power plants. At present, the domestic mainstream denitration technology contains Selective Catalytic Reduction (SCR), Selective Non-catalytic Reduction (SNCR) and SNCR/SCR mixed denitration technology, etc. Each kind of technology has advantages and disadvantages, under the influence of many factors such as economy, technology, environmental protection. Some factors are qualitative and some are quantitative, therefore, how to evaluate the denitration technology in a scientific and reasonable way has always been a problem. However, in China, scientific optimization of denitration technology is not only benefit for the promotion of the denitration devices but it plays an important role in the formulation of the denitration price.

At present, the evaluation methodology and optimization model on denitration technology contain Analytic Hierarchy Process, Fuzzy Comprehensive Evaluation[1,2] and Gray System Theory[3,4]. With
reference to a large number of related articles, this paper builds a combined evaluation model based on Fuzzy Comprehensive Evaluation and Gray Relational Analysis. Through Fuzzy Comprehensive Evaluation it achieves the reasonable conversion from qualitative to quantitative and through Gray Relational Analysis it sets the weight of each index, which making sure that the evaluation model is scientific and rational. Then, with the combined evaluation model, it evaluates the performance of three kind of denitrification technology(SCR, SNCR, SNCR/SCR.). The evaluation result verifies the effectiveness and practicality of the model. And meanwhile, it could be a valuable reference for the promotion of the denitrification devices and the formulation of the denitrification price.

2. Gray-Fuzzy combined comprehensive evaluation model

Fuzzy Comprehensive Evaluation is on the basis of fuzzy mathematics. By using the fuzzy theory, some qualitative factors are converted to quantitative factors. To reflect the importance of the factors, every factor should be applied a weight. Weights have a significant effect on the result of the evaluation, sometimes, different weights will lead to a complete opposite conclusion. Gray Relational Analysis is a branch of Gray system theory, it can solve the problem of weight distribution [5].

2.1. Fuzzy Comprehensive Evaluation model

The theory of Fuzzy Comprehensive Evaluation is: Dividing all factors into several subsets according to attributive character and then primarily comprehensive evaluating the several factor subsets. Finally, get the ultimate evaluate conclusion through evaluating the primary comprehensive evaluations. General procedure is as follows:

1. **Determine the evaluation object's universe of discourse**
   
   $U = \{u_1, u_2, \ldots, u_m\}$
   
   It means there is $m$ evaluation indexes, that is to say we evaluate the objects from $m$ aspects.

2. **Determine the remark grade's universe of discourse**
   
   The remark grade's universe of discourse is the sets of the object's evaluation results, and indicated by $V$:
   
   $V = \{v_1, v_2, \ldots, v_n\}$
   
   $v_i$ means the evaluation result of number $i$, $n$ means the number of total evaluation results.

3. **Evaluate the factors and construct fuzzy relational matrix $R$**
   
   Quantify the objects' every factor, that is to determine the object's membership grade of each level fuzzy subsets, and then get the fuzzy relational matrix:
   
   $$R = \begin{bmatrix}
   r_{11} & r_{12} & \cdots & r_{1n} \\
   r_{21} & r_{22} & \cdots & r_{2n} \\
   \vdots & \vdots & \ddots & \vdots \\
   r_{m1} & r_{m2} & \cdots & r_{mn}
   \end{bmatrix}$$

4. **Determine fuzzy weight vector of evaluation factors**
To reflect the importance of the factors, every factor should be applied a weight. \( a_i \) indicate the weight of factor \( i \), and \( I \geq a_i \geq 0; \sum a_i = I \), matrix \( A=(a_1 \ a_2 \cdots \ a_m) \). This essay determine factor weights by Gray Relational Analysis, see 1.2 in detail.

5. Multi-stage fuzzy comprehensive evaluation

Multi-stage fuzzy comprehensive evaluation model is: Composite matrix \( A \) and the fuzzy relational matrix \( R \) with appropriate composition operator, and get the evaluation results of fuzzy comprehensive evaluation vector \( B \).

\[
B = A \odot R = (a_1 \ a_2 \cdots \ a_m) \odot \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{pmatrix} = (b_1, \ b_2, \cdots, \ b_n)
\]

6. Evaluation results analysis

Compare the objects' evaluation results and sequence them, that is to convert the comprehensive evaluation results \( B \) to comprehensive grades and then get the best one.

2.2. Gray Relational Analysis

In this paper, the weight of each index is determined by Gray Relational Analysis. Take the first grade index weights determination as an example, follow these steps [6]:

1. Determine index set of importance

Index set \( S= (S_1, S_2 \ldots \ S_e) \), \( S_j \) is the importance level \( j \), \( e \) is the number of importance level.

2. Determine the index importance degree and the reference sequence

The obtain of determination of the reference sequence is through experts scoring the importance of the indexes. Reference sequence \( U_0 = \{e_{max1}, e_{max2}, \cdots, e_{maxn}\} \), \( e_{max} = \max\{e_{k1}, e_{k2}, \cdots, e_{kn}\} \)

\( k=1,2,\ldots,m \) ; \( e_{ij} \) means the importance grades of index \( j \) scored by expert \( i \). \( U_i = \{e_{i1}, e_{i2}, \cdots, e_{ki}\} \) ( \( i=1,\ldots,n \) ) is importance grades vector of index \( i \).

3. Relational degree calculation

Relational degree coefficient can be calculated by formula (1).

\[
\xi_j(k) = \frac{\min_{i,k} \min_i |U_0(k) - U_i(k)| + \rho \cdot \max_{i,k} \max_i |U_0(k) - U_i(k)|}{|U_0(k) - U_i(k)| + \rho \cdot \max_{i,k} \max_i |U_0(k) - U_i(k)|}, \quad (1)
\]

\( i = 1, 2, 3 \quad k = 1, 2, \cdots, 10 \)

In this formula, \( \rho \) is resolution ratio, \( \rho \in [0,1] \). It can reduce the effects of calculation from extremum value. In general, \( \rho = 0.5 \).

Relational degree directly reflects the pros and cons of the relative sequence to the reference sequence, the mathematical model is;
4. Weights calculation

Through formula (3), normalized the relational degree of the above and get first level weight set A=(A₁, A₂… Aₙ).

\[ A_i = \frac{m_i}{\sum_{i=1}^{n} m_i} \quad i = 1, 2, \ldots, n \]  

Similarly, we can get the weights of second level weight set Aᵢ=(Aᵢ₁, Aᵢ₂… Aᵢₙ).

3. Gray-Fuzzy combined comprehensive evaluation of deNOx technology

Flue gas denitrification technology analysis is a systematic strong and wide range evaluation work, it contains the determination of evaluation index and evaluation model [7]. The current relatively mature flue gas denitrification technology contains: A. Selective Catalytic Reduction method (SCR); B. Selective Non-catalytic Reduction method (SNCR); C. SNCR/SCR method. We analyse the technical and economic characteristics of these denitrification technologies. The comprehensive performance analysis of the three flue gas denitrification technology are showed at Table 1.

3.1. Determine the evaluation factor set

The index set can be determined according to the system of evaluation indexes above, as fig 1 shows.

3.2. Determine the degree of membership

1. Quantitative indexes

(1) Denitration efficiency. According to general denitration requirements, the constraint condition for denitration efficiency is \(25\% \leq X\% \leq 100\%\), so the membership function is linear.

\[ \mu_{1i}(X) = \begin{cases} 0, & X \leq 25 \\ \frac{X - 25}{100 - 25}, & 25 \leq X \leq 100 \end{cases} \]  

(2) The escape rate of NH3. With the description of lower semi-trapezoid distribution, it is

\[ \mu_{2i}(X) = \begin{cases} 1, & X \leq 3 \\ \frac{13 - X}{13 - 3}, & 3 \leq X \leq 13 \end{cases} \]  

(3) System operation cost. The experts assessed, if unit of system operation cost is lower than 0.3, the degree of the membership is 0; if unit of system operation cost is higher than 3, the degree of the membership is 1. Therefore, the function of system operation cost is;
\[
\mu_{12}(X) = \begin{cases} 
0, & X \leq 0.3 \\
\frac{3 - X}{3 - 0.3}, & 0.3 < X \leq 3 \\
1, & X > 3 
\end{cases}
\]  \hspace{1cm} (6)

Table 1. The comprehensive performance analysis of three kinds of flue gas denitration technology.

<table>
<thead>
<tr>
<th>Evaluation index</th>
<th>SCR</th>
<th>SNCR</th>
<th>SCR/SNCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denitration efficiency (%)</td>
<td>70~90</td>
<td>25~40</td>
<td>55~90</td>
</tr>
<tr>
<td>Is Leading to SO₂/SO₃ oxidation</td>
<td>Yes</td>
<td>No</td>
<td>Yes but lower</td>
</tr>
<tr>
<td>Whether for the new power plants</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Is suitable for old factory reform</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Whether the product is recovery or not</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Technical complexity</td>
<td>more complex</td>
<td>complex</td>
<td>Relatively simple</td>
</tr>
<tr>
<td>Process maturity</td>
<td>Mature</td>
<td>More mature</td>
<td>General</td>
</tr>
<tr>
<td>The escape rate of NH₃ (ul·L⁻¹)</td>
<td>3~5</td>
<td>10~15</td>
<td>4~13</td>
</tr>
<tr>
<td>The influence for air preheater</td>
<td>Big</td>
<td>Small</td>
<td>Smaller</td>
</tr>
<tr>
<td>The loss of System pressure</td>
<td>Big</td>
<td>No</td>
<td>Small</td>
</tr>
<tr>
<td>The influence of fuel</td>
<td>Catalyst wear, passivation</td>
<td>No</td>
<td>Catalyst wear, passivation</td>
</tr>
<tr>
<td>The influence of the boiler</td>
<td>Temperature</td>
<td>Temperature, velocity, NOx</td>
<td>Temperature, velocity, NOx</td>
</tr>
<tr>
<td>Investment cost</td>
<td>High</td>
<td>Low</td>
<td>Middle</td>
</tr>
<tr>
<td>System operation cost (Yuan·t⁻¹)</td>
<td>1.3</td>
<td>0.8</td>
<td>1.1</td>
</tr>
<tr>
<td>Covers space</td>
<td>Big</td>
<td>Small</td>
<td>Medium</td>
</tr>
<tr>
<td>Catalyst consumption</td>
<td>Much</td>
<td>No</td>
<td>Little</td>
</tr>
<tr>
<td>Cost of new power plant (Yuan·t⁻¹)</td>
<td>70</td>
<td>15</td>
<td>42.5</td>
</tr>
<tr>
<td>The transformation cost of old power plant(Yuan·t⁻¹)</td>
<td>100</td>
<td>15</td>
<td>90</td>
</tr>
</tbody>
</table>

(4) As similar as system operation cost, the function of cost of new power plant is;

\[
\mu_{25}(X) = \begin{cases} 
0, & X \leq 5 \\
\frac{100 - X}{100 - 5}, & 5 < X \leq 100 \\
1, & X > 100 
\end{cases}
\]  \hspace{1cm} (7)

(5) Similarly, the function of transformation cost of old power plant is;
The degree of membership determination for qualitative indexes is through expertising. The qualitative indexes are divided into five levels, namely excellent, good, fair, poor, and bad. If the factor is excellent, the value of the index is 0.9; if the factor is good, the value of the index is 0.7; if the factor is fair, the value of the index is 0.5; if the factor is poor, the value of the index is 0.3; if the factor is bad, the value of the index is 0.1; when the factor value is between two levels, and then the evaluation value obtained is between the two rating values.

At last, normalized the degree of membership evaluation, the results are showed in table 2.

Table 2. The factor set of evaluation index.

<table>
<thead>
<tr>
<th>Evaluation index</th>
<th>Weighted function</th>
<th>SCR</th>
<th>SNCR</th>
<th>SCR/SNCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denitrification efficiency</td>
<td>0.65</td>
<td>0.612</td>
<td>0.068</td>
<td>0.22</td>
</tr>
<tr>
<td>Oxidation degree SO2/SO3</td>
<td>0.1</td>
<td>0.169</td>
<td>0.513</td>
<td>0.318</td>
</tr>
<tr>
<td>Whether for the new power plants</td>
<td>0.08</td>
<td>0.5</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>Is suitable for old factory reform</td>
<td>0.08</td>
<td>0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Whether the product is recovery or not</td>
<td>0.09</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
3.3 Determine index weights

1. Determine index set of importance.

2. Determine the index importance degree and the reference sequence (see Table 3).

Table 3. The score of important degree and the reference series of one class index.

<table>
<thead>
<tr>
<th>Expert</th>
<th>Environment</th>
<th>Technology</th>
<th>Economic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Reference sequence U₀

3. Relational degree calculation (see Table 4).

Table 4. Each index correlation coefficient.

<table>
<thead>
<tr>
<th>Expert</th>
<th>( \xi_1 )</th>
<th>( \xi_2 )</th>
<th>( \xi_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.71429</td>
<td>0.23810</td>
<td>0.26316</td>
</tr>
<tr>
<td>2</td>
<td>1.00000</td>
<td>0.21739</td>
<td>0.23810</td>
</tr>
<tr>
<td>3</td>
<td>1.00000</td>
<td>0.26316</td>
<td>0.23810</td>
</tr>
<tr>
<td>4</td>
<td>0.71429</td>
<td>0.26316</td>
<td>0.26316</td>
</tr>
<tr>
<td>5</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
</tr>
<tr>
<td>6</td>
<td>1.00000</td>
<td>0.26316</td>
<td>0.21739</td>
</tr>
<tr>
<td>7</td>
<td>1.00000</td>
<td>0.23810</td>
<td>0.21739</td>
</tr>
<tr>
<td>8</td>
<td>1.00000</td>
<td>0.26316</td>
<td>0.21739</td>
</tr>
<tr>
<td>9</td>
<td>1.00000</td>
<td>0.23810</td>
<td>0.23810</td>
</tr>
</tbody>
</table>

Correlation coefficient mean

4. Weights calculation

\[ A = (0.66, 0.17, 0.17) \]

5. Determine the weights of second level.

\[ A_E = (0.65, 0.10, 0.08, 0.08, 0.09) \]

\[ A_T = (0.32, 0.21, 0.27, 0.03, 0.07, 0.06, 0.04) \]

\[ A_{EC} = (0.21, 0.19, 0.17, 0.23, 0.15, 0.05) \]

3.4 Primary comprehensive evaluation
We can make primary comprehensive evaluation for environment index of SCR, as follow shows:

\[ E_{\text{SCR}} = A_E \cdot R_{E \cdot \text{SCR}} = (0.65, 0.10, 0.08, 0.08, 0.09) \cdot (0.612, 0.169, 0.500, 0.000, 0.000) = 0.454 \]

Similarly, we can get the result of primary evaluation matrix:

\[
\begin{pmatrix}
0.454 & 0.136 & 0.255 \\
0.465 & 0.215 & 0.316 \\
0.217 & 0.463 & 0.319
\end{pmatrix}
\]

3.5. Secondary evaluation

The result of multi-stage fuzzy comprehensive evaluation of deNOx technology is:

\[
B = A \cdot R = (0.66, 0.17, 0.17) \cdot \begin{pmatrix}
0.454 & 0.136 & 0.255 \\
0.465 & 0.215 & 0.316 \\
0.217 & 0.463 & 0.319
\end{pmatrix} = (0.416, 0.205, 0.276)
\]

3.6. The result of evaluation of deNOx technology

From the result of the evaluation, we get the conclusion: \( \text{SCR} \succ \text{SNCR} / \text{SCR} \succ \text{SNCR} \).

4. Conclusion

This paper established the Gray-Fuzzy Comprehensive evaluation model. Make use of the Gray Relational Analysis to determine the evaluation index's weights while using the fuzzy comprehensive evaluation method to make comprehensive evaluation, which makes the model more scientific and reasonable. A reasonable denitration technology optimization plays an vital role in the formulation of denitration price and the power engineering construction. The case shows that the combination model for denitration technology optimization has practical value.

The results show that selective catalytic reduction (SCR) method is better than SNCR/SCR mixed denitration method, and SNCR/SCR mixed denitration method is better than the selective non-catalytic reduction (SNCR). It is in accordance with the reality of the application of the denitration technology nowadays.

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6. Reference


