Low_NOx emission and high efficiency combustion optimization for opposed firing boiler BASED on intelligent algorithm

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Abstract. On the basis of BP-GA algorithm for boiler efficiency and NOx emission concentration, a combustion simulation model was established. By learning the training samples based on low NOx combustion adjustment tests, the combustion simulation model can accurately map the nonlinear relationship between boiler operation parameters and boiler efficiency and NOx emission concentration. Genetic algorithm was used to obtain the optimization strategies to get the best boiler efficiency and NOx emission concentration, which provides guidance for the operation.

1. Introduction
As the country's environmental policy is increasingly strict, the technology of low_NOx emission combustion and high efficiency SCR (Selective Catalytic Reduction) has been widely applied in coal-fired power plants, the NOx emission concentration of coal-fired boilers decreased significantly [1]. However, the combustion is a very complex nonlinear physical and chemical process, many tests show that for the same boiler burning equipment with same kind of coal, the different operation modes can cause significant differences in the NOx emission concentration of the economizer outlet, and also affect the boiler thermal efficiency. So the optimization of low_NOx combustion is important, but it is also limited by human, material and operating conditions. In this paper, artificial neural network model is built to describe the effect of operating parameters on NOx emission concentration and boiler efficiency Genetic algorithm is applied to optimize and simulate the combustion process of boiler efficiency and NOx emission concentration. The results show that the application of genetic algorithm and BP neural network algorithm for the boiler combustion optimization is effective, and better boiler efficiency and NOx emission concentration can be obtained.

2. Combustion optimization test after low_NOx transformation project
The 330MW unit boiler of a power generation company was designed by Beijing Babcock Willcocks Co., Ltd., including sub critical parameters, intermediate reheat, opposed wall firing combustion, separated bellows and solid slag discharging coal drum boiler. In 2013, low_NOx burner and air graded combustion technology were used in low_NOx combustion transformation project. The original 5 layer DRB burners were reformed. The A B C burners were replaced by Air Jet burners. The
DE burners were replaced by DRB-4Z burners. According to the ignition characteristics of new DRB-4Z and Air Jet low_NOx burner, many tests were made in the adjustment of burner swirl intensity and air distribution ratio. With the principle of single factor and orthogonal test, in multiple load conditions, combustion optimization tests were made to find the optimal oxygen, wind coal ratio, air distribution mode, in order to obtain the optimum results of NOx emission and boiler efficiency. After screening, 30 typical representative working conditions are obtained as BP neural network modeling data, and part of the data are shown in table 1.

### Table 1. Combustion adjustment test samples.

| Parameter                           | Samples |
|-------------------------------------|---------|
|                                     | 1       | 10     | 15     | 20     | 22     | 30     |
| Unit load (MW)                      | 329     | 270    | 177    | 256    | 182    | 182    |
| Total fuel (t.h⁻¹)                  | 176     | 136    | 87     | 146    | 103    | 103    |
| A air damper (%)                    | 45      | 35     | 30     | 29     | 23     | 34     |
| B air damper (%)                    | 44      | 34     | 15     | 30     | 25     | 31     |
| C air damper (%)                    | 15      | 25     | 14     | 23     | 30     | 25     |
| D air damper (%)                    | 38      | 15     | 29     | 35     | 22     | 30     |
| E air damper (%)                    | 40      | 35     | 30     | 35     | 25     | 35     |
| OFA1 damper (%)                     | 100     | 100    | 70     | 80     | 70     | 70     |
| OFA2 damper (%)                     | 100     | 100    | 70     | 80     | 80     | 90     |
| secondary air pressure (KPa)        | 1.02    | 0.77   | 0.28   | 0.46   | 0.31   | 0.30   |
| primary air pressure (KPa)          | 9.89    | 9.27   | 7.89   | 0.36   | 8.92   | 9.11   |
| Oxygen (%)                          | 1.0     | 2.75   | 4.90   | 2.10   | 4.55   | 4.62   |
| NOx (mg.m⁻³)                        | 319     | 258    | 255    | 285    | 321    | 319    |
| Boiler efficiency (%)               | 92.11   | 91.82  | 91.94  | 91.77  | 91.95  | 92.08  |

### 3. Modeling and simulation of BP neural network in combustion process

The BP algorithm, the error back propagation algorithm, is one of the widely used methods in neural network learning. [2] In the BP algorithm, the output and sample values obtained from the neural computation are used for error analysis. The weights of the neural network are repeatedly corrected, so that the output of the network is close to the desired output, and the final error meets the requirement. This model has the characteristics of high prediction precision, strong generalization ability and wide application.

#### 3.1. Input and output factors setting of network model

According to the combustion principle and the combustion optimization test, the controllable factors affecting the boiler efficiency and NOx emission concentration are analyzed. The difference of coal quality directly affects the combustion efficiency. The basic data of coal quality include elemental analysis and calorific value. Because the coal element analysis cannot be carried out at power plant, the total coal and unit load are set to be input factors. Although the control of oxygen content, secondary air dampers are the key of the low_NOx combustion and the graded combustion technology, so the primary air pressure, secondary air pressure, oxygen content of the economizer outlet and the secondary air dampers and the OFA air dampers are used to be the input factors. All the input factors are 12 together. The NOx emission concentration of the economizer outlet and the boiler efficiency are set to be output factors. In order to ensure that the model does not cause convergence due to the data discrepancy and magnitude difference, and the model correctly reflects the relation between the input and output variables, we need to normalize the input and output data to [-1,1] intervals.
3.2. Network model design and optimization

3.2.1. Network model design. Three layer BP neural network is used to build the simulation model of the combustion process. The input layer is used as the input buffer of samples, and the neuron activation uses ‘Logsig’ transfer function. [3] The number of neurons is 12. The hidden layer is the core of the BP network. It realizes the nonlinear mapping of input parameters to output parameters, and the activation uses ‘Logsig’ transfer function. The number of neurons is 25. The ‘Purelin’ linear transmission function is selected for the activation function of the output layer neuron, and the number of neurons is 2. The BP network training function uses back propagation algorithm ‘Trainlm’ function. The deviation learning function uses ‘Learngdm’ function of gradient descent weight learning algorithm with additional momentum factor, and the performance evaluation function uses the ‘MSE’ algorithm of the mean square error performance algorithm. Network convergence error uses $1 \times 10^{-8}$.

3.2.2. Network model optimization. The selection of BP neural network structure, initial connection weights and thresholds have great influence on network training, which directly affects the convergence speed, global convergence and simulation accuracy. In this paper, the genetic algorithm is used to optimize the BP network with population 50, genetic algebra 100. Through coding and decoding population initialization and fitness calculation of network weight and threshold, BP network model is optimized, and the better network initial values and threshold values are obtained. This algorithm combined GA with BP, which is called GA+ BP algorithm and it realized the combination of global search capability of GA and local optimize performance of BP algorithm.

3.3. Network model training and simulation

3.3.1. Network model simulation. The 27 groups of data in table 1 are taken as training samples, and the remaining 3 groups are taken as test samples, and the expected accuracy is achieved after network training. The simulation results are shown in figures 1 and 2, and the relative error of simulation is shown in figures 3 and 4. Samples 1, 10, and 22 are the test data under high, medium and low load conditions and the rest are training samples. After training, the network model can accurately predict the actual physical conditions. Relative error is defined as follow:

$$\delta = \frac{\gamma_{\text{simulated}} - \gamma_{\text{measured}}}{\gamma_{\text{measured}}}$$  \hspace{1cm} (1)

Where $\delta$ is the relative error, $\gamma_{\text{simulated}}$ is the simulated value of the model, and $\gamma_{\text{measured}}$ is the measured value of parameter.

![Figure 1. efficiency simulating curve.](image1)

![Figure 2. NOx emission simulating curve.](image2)
In the simulation of boiler efficiency, the maximum absolute simulation deviation of the training sample is 0.04% and the maximum relative error is 0.05%, the maximum absolute simulation deviation of the test sample is 0.21% and the maximum relative error is 0.23%. In the simulation of NOx emission concentration, the maximum absolute simulation deviation of training samples is 3.01mg/m³, the maximum relative error is 1.21%, the maximum absolute simulation deviation of test samples is 11.01mg/m³, and the maximum relative error is 3.73%. According to the rules of GB/T10184-2015 Performance test code for utility boiler, the maximum error is not only acceptable in the scope of engineering application, but also high in precision.

3.3.2. Network generalization ability. Whether the neural network is excellent is not only reflected in its ability to fit the existing data, but also to the ability of predicting the new data. That is generalization ability. There are some contradictions between the generalization ability and the training ability of the network. When the training ability is poor, the prediction ability is also poor, with the improvement of training ability, the prediction ability is also improved. When the limit is reached, the prediction ability decreases with the improvement of the training ability, that is the so-called ‘over fitting’ phenomenon.

According to the principle of low_NOx combustion technology and the test rule, in many controllable operation parameters, the control of OFA dampers opening and combustion oxygen are the most obvious impact on NOx generation. The sample data 1 is a result of oxygen optimization test. When other parameters are constant, reduce the inlet damper of feed fans, the secondary pressure decreased from 1.25KPa to 1.02KPa, the oxygen content was reduced from 1.51% to 1.01%, and the less oxygen combustion in the furnace resulted in the intensification of the reductive atmosphere and the increase of carbon content in the fly ash. The measured NOx values are reduced from 345mg/m³ to 319mg/m³, and the measured boiler efficiency is reduced from 92.37% to 92.11%. According to the simulation results of test sample 1, the simulation value of NOx is 330 mg/m³, and the simulation value of boiler efficiency is 92.02%. Similarly, the samples data 10 and 22 are all the results of secondary damper optimization tests. The simulation results of three test samples have verified the generalization ability and accuracy of BP network optimized by genetic algorithm.

4. Genetic algorithm combustion optimization
Genetic algorithm is a widely used method based on the survival of the fittest mechanism in the process of biological evolution, the information exchange rules within the population, and the complex optimization problems [1,6]. The basic operations include fitness functions, coding, selection, crossover, and mutation. In this paper, on the base of BP network combustion simulation model, the genetic algorithm is used to find the optimal operation parameters for the best boiler efficiency and NOx emission in real time, which provides guidance for the operation.
4.1. Selection of fitness function
The genetic algorithm does not use the external information in the evolutionary search, and only uses the fitness of each individual in the population to search. The fitness function is the key to the optimization of genetic algorithm, which directly affects the convergence speed of genetic algorithm and the finding of the optimal solution. Based on the analysis of low_NOx combustion technology, there is a certain exclusion between boiler efficiency and NOx emission of economizer outlet. Good low_NOx combustion results at the expense of boiler efficiency. The essence of boiler combustion optimization is to find the compatible operation parameters which cause the best boiler efficiency and NOx concentration of economizer outlet at the same time. The fitness goal function is defined as follow:

\[ \min z = a \times NOx + b \times (1 - \eta) + K \]  

Where \( z \) is result of fitness goal function, \( NOx \) is the emission concentration of economizer outlet, and \( \eta \) is the boiler efficiency, a and b is the coefficient based on the value of attention to efficiency and emission concentration, K is the constant.

4.2. Combustion optimization analysis
The genetic algorithm based on the BP network combustion simulation model is used to optimize the combustion simulation under the working condition of the unit 330MW. The population number is 50, the cross probability is 0.8, the mutation probability is 0.2, the weight of the target function a and b are selected as 0.4 and 0.6 respectively, and the choice of evolutionary algebra is 50. From the fitness function curve of figure 5, we can see that the average fitness curve has the same trend with the best fitness curve. At the time of 30 evolution generation, the two curves basically coincide, the best optimization is achieved.

![Figure 5. fitness curve.](image_url)

The optimization results are as shown in table 2. Before optimizing, the uniform air distribution was adopted, the secondary air dampers of A B D E were about 65%, the OFA dampers were about 80% and the oxygen was about 3.1%. After optimizing, the secondary air dampers corresponding to Airjet type burner were closed to 25%, the secondary air dampers corresponding to DRB-4Z type burner were closed to 36%, the OFA dampers were opened to 100%, oxygen content was controlled to 1.13%. With the optimization strategy, NOx emission concentration of economizer outlet decreased from 348 mg/m\(^3\) to 289 mg/m\(^3\), the boiler efficiency was reduced from 92.37% to 92.02%.

The optimization strategy guidance basically accords with the combustion optimization optimal training condition. The secondary air pressure and the air distribution mode also correspond to the fitting oxygen. When the operator actually controls, the oxygen demand should be more referenced.
Table 2: Combustion optimization tests data.

| Parameter                  | Before optimization | After optimization |
|----------------------------|---------------------|---------------------|
| Unit load (MW)             | 330                 | 330                 |
| Total fuel (t.h⁻¹)         | 176                 | 175                 |
| A air damper (%)           | 65                  | 25                  |
| B air damper (%)           | 64                  | 25                  |
| C air damper (%)           | 20                  | 20                  |
| D air damper (%)           | 68                  | 36                  |
| E air damper (%)           | 60                  | 35                  |
| OFA1 damper (%)            | 80                  | 100                 |
| OFA2 damper (%)            | 80                  | 100                 |
| Secondary air pressure (Kpa)| 1.35                | 1.11                |
| Primary air pressure (Kpa) | 9.91                | 9.81                |
| Oxygen (%)                 | 3.10                | 1.13                |
| NOx (mg.m⁻³)               | 348                 | 289                 |
| Boiler efficiency (%)      | 92.37               | 92.02               |

5. Conclusions
In this paper, based on the test data of boiler low NOx combustion optimization, the BP neural network combustion model can accurately map the nonlinear relationship between boiler controllable operation parameters and boiler efficiency and NOx emission concentration.

The net structure and initial weights and threshold of BP neural network selection have great impact on network training, directly affect the network convergence speed, global convergence and network simulation precision. Using genetic algorithm to optimize BP network, we can get better network initial values and threshold values, and get a network model with strong generalization ability and accurate prediction.

Basing on the BP neural network combustion simulation model, we selected the appropriate fitness function, converted the two optimization indexes including the boiler efficiency and NOx emission concentration into a comprehensive index. With the use of genetic algorithm in combustion optimizing, we get a set of operation optimization strategies to obtain the best boiler efficiency and the economizer outlet NOx emission concentration. The optimization method can provide guidance for operation.

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