The Integrated System Optimization based on the Boiler Combustion and Denitration with Denitration Operating Cost Consideration

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ABSTRACT—At present, in the thermal power stations, it always cost a lost to operate the boiler combustion system and the flue gas denitrification system. Under the premise in standard emission, it can improve the power units' economic performance by optimizing the comprehensive operating cost of the boiler combustion system and denitrification system. This paper has used LSSVM to build the model of the boiler combustion system and denitrification system. Furthermore, the genetic algorithm is applied to optimize the integrated cost on-line. For different working conditions, under the constraints of safety and environment protection, the minimal integrated cost is the optimizing target to prevent the SCR cost from reducing. At last, the result shows that the optimized cost has reduced a lot as well as the SCR cost. Otherwise, the NOx emissions in the SCR output has been lowered and met the policy requirement, and that the boiler efficiency is improved significantly**. In conclusion, this paper has successfully built a integrated system based on the boiler combustion and denitrification, which has good performance in environment friendly and economic benefit.**

Keywords-boiler combustion; SCR; integrated model; GA; LSSVM; integrated economy; optimization

I. INTRODUCTION

The nitrogen oxides (NOx) produced in coal-fired power plant is a kind of typical polluting gas. At present, it is still a tough challenge for our society to achieve "Energy Saving and Emission Reduction". In recent years, for making the atmosphere quality better, the power generation enterprises have been researched on improving the boiler's efficiency and decreasing the coal consumption. As well, the national standards are totally implemented to decrease NOx emission. So far now, there are mainly two technologies to reduce the amount of NOx in the flue gas, one of them is the low nitrogen combustion technology, the other one is to install the denitrification system in the tail flue. Meanwhile, the SCR is a kind of advanced technology. The SCR denitration is a technology which will install the denitration device in the flue end to convert the NOx in the gas into innocuous substance.

To satisfy the new emission standard, and fully consider the safety and cost-effectiveness, the coal-fired units will apply the technologies of low nitrogen combustion and denitration unit installation[1]. However, these two technologies respectively produces its own extra cost, and these cost have an inversely proportional relationship to each other[2]. Therefore, minimizing total cost and controlling the NOx emission will be the effective means for thermal power plants to gain environmental and economic benefits.

The least squares support vector machine is a new type of machine learning algorithms based on the theory of statistics, which has unique superiority in small samples modeling[3]. In lots of research work, LSSVM performs well in modeling the boiler combustion system and SCR denitration efficiency[4]. Nevertheless, seldom integrated study about the boiler combustion and denitrification system have been processed from the whole perspective. As a consequence, it has significant meaning to fully combine these two systems to achieve the low emission and economic optimization.

II. INTRODUCTION TO THE LSSVM

The support vector machine(SVM) is a new machine learning algorithm based on the statistical theory, which has good performance in small sample modeling. The least squares support vector machine （LSSVM）proposed by Suykens is a specific form of the SVM. It can transfer the quadratic programming problem in SVM model training into a linear programming problem which all based on the KKT conditions. Because of this approach, the calculated amount and modeling time have both been shortened. The training samples $T=\{(x_i,y_i),x\in R^d,y\in R,i=1,\dots n\}$, is mapped into the high-dimensional feature space by nonlinear mapping $\varphi(\cdot)$, to construct the decision functions in new sample space as showed in (1)

$$f(x)=\omega^T\cdot\varphi(x)+b \qquad (1)$$

The model parameter ω and b are determined by the Structural Risk Minimization, showed in (2)

$$R=\frac{1}{2}\|\omega\|^2+c\cdot R_{emp} \qquad (2)$$

The square error R_{emp} is selected as the control function, and then the Lagrange conditional extreme is used to construct the following function in (3) :

$$L(x,\alpha)=\frac{1}{2}\|\omega\|^2+c\sum_{i=1}^{n}e_i^2+\sum_{i=1}^{n}\alpha_i(y_i-\omega^T\cdot\varphi(x_i)-b-e_i) \qquad (3)$$

Based on the KKT condition, to make the extreme solutions satisfy the following relationship in (4):

$$\frac{\partial L}{\partial\omega}=0,\quad \frac{\partial L}{\partial b}=0,\quad \frac{\partial L}{\partial e_i}=0 \qquad (4)$$

The kernel function is $\varphi(x_i)\cdot\varphi(x_j)=K(x_i,x_j)$ and then solved by the Lagrangian function. Finally to get the values of parameter α and b by least square method and determine the model decision-making function as followed in (5):

$$f(x)=\sum_{i=1}^{n}\alpha_i K(x_i,x_j)+b \qquad (5)$$

III. THE PRINCIPLE OF SCR DENITRATION

The SCR denitration is an efficient technology which is widely used in reducing the NOx in gas. It import the reductant(ammonia or liquid ammonia) and air into the SCR reactor. In presence of catalyst, the NH3 and the NOx will react into the N2 and H20, the principle is as the Fig.1, the chemical equation is as showed in (6)

$$4NO+4NH_3+O_2=4N_2+6H_2O$$
$$2NO_2+4NH_3+O_2=3N_2+6H_2O \qquad (6)$$
$$6NO+4NH_3=5N_2+6H_2O$$
$$6NO_2+8NH_3+O_2=7N_2+12H_2O$$

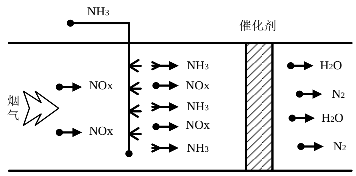


Figure1. SCR denitration reaction mechanism

The SCR has excellence performance in NOx removal efficiency. Moreover, the NOx reduction reaction will take place under certain temperature condition and catalyst. But during the reaction process, the catalyst activity will reduced due to the contact with the gas. So that, the catalyst need to be replaced regularly. In additional, being as served as the amino-reductant, the enterprises should choose their own suited reductant to reduce the cost of denitration.

IV. THE INTEGRATED MODEL OF BOILER COMBUSTION AND DENITRIFICATION SYSTEM

The object of this study is a supercritical once-through tangentially fired boiler, the furnace is equipped with six layers of secondary air(A、B、C、D、E、F), two layers of COFA and four layers of SOFA. The reducing agent of the denitrification device is liquid ammonia.

A. The whole structure of the model

During the thermal power unit operation, the SCR denitration system is a part of the boiler air and gas system. Its input are the NOx emissions in the boiler output, the temperature in the boiler output[5]. This paper has combined the boiler combustion model with the SCR denitration efficiency model, showed in the Fig.2. It has been improved that the SCR efficiency model can well describe the SCR system operating state[6]. The NOx emissions in the SCR output can be calculated by the SCR efficiency and the NOx concentration in the boiler output.

So that, this paper has set the output of the boiler combustion model to be the input of the SCR denitration efficiency model. Moreover, the ammonia spraying amount is regard as the adjustment amount to control the NOx concentration in the SCR output, which can achieve the high-efficiency of the boiler and the low-cost of the coal consumption and denitration.

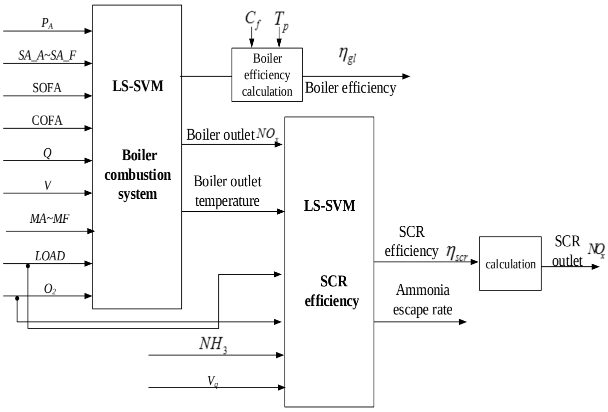


Figure 2. The whole structure of the integrated system model

B. The selection of the input variables

Through the arrangement form of the boiler and SCR, unit load (*Load*), 6 layers of secondary air damper positions (*SA_A~SA_F*), 4 layers of SOFA throttle opening (*SOFA1~SOFA4*), 2 layers of COFA throttle opening (*COFA1~COFA2*), the calorific efficiency of coal (*Q*), primary air pressure (P_A), the volatility of the fuel (*V*), oxygen content in flue gas (O_2) and 6 layers of coal feeder opening (*MA~MF*), carbon contained in fly ash C_f, temperature of flue gas T_p, a total of 25 variables inputs for boiler combustion model.

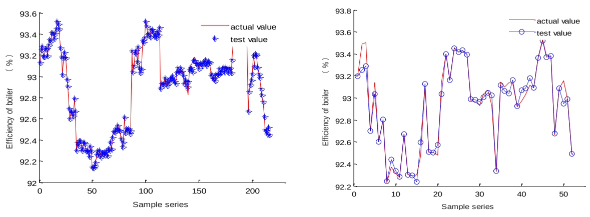
Units Load(*Load*), oxygen content in flue gas(O_2), NOx concentration in the boiler output, exhaust gas temperature(T_p), ammonia spraying amount(NH_3) and Gas flow(V_q) are used as the input of the SCR denitration efficiency model; The boiler combustion efficiency η_{gl} and the SCR denitration efficiency η_{scr} are used as the output of the integrated model. Afterwards, 269 sets of steady-state data were extracted from the power plant SIS system to prepare for modeling.

C. The establishment of the integrated model.

LSSVM is used to build the boiler combustion and denitration integrated system model. Moreover, the 216 sets of data are selected as the training data, and the rest 52 sets are selected as the test data, which are used to verify the model reaction boiler combustion and SCR work. In the following, the genetic algorithm is used to optimize the kernel function σand regularization parameters c. Based on the denitration efficiency formula, the NOx concentration in the boiler output is the main index of calculating the NOx concentration in the SCR output, that is Formula (7):

$$NOx_{SCR\_out} = (1-\eta_{SCR}/100)\times NOx_{SCR\_in} \tag{7}$$

The Fig.3 and Fig.4 show the contrast between the measured value and the predicted value, where are adopt from the boiler combustion and denitration integrated model's training sample and test sample. The NOx concentration in the SCR output is predicted by the SCR efficiency and NOx concentration in the boiler output.



(a) Training data (b) Testing data

Fig.3. Prediction of Boiler Efficiency by Integrated Model

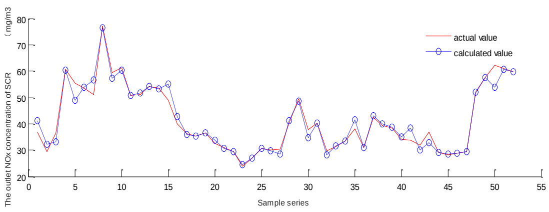


Figure 4. Prediction SCR outlet NOx by Integrated Model

Based on the calculation, the boiler efficiency MAE=0.0383， δ%=0.0412%, and the NOx concentration in SCR output MAE=1.166， δ%=1.846%. The model's forecast results have the same trend with the true value and less prediction error.

Therefore, the integrated model can well predict the boiler combustion and denitration integrated system, when has good performance in predicting the NOx concentration in SCR output, boiler combustion efficiency, and ammonia escape rate. The further research is described in the following article.

V. ECONOMICAL OPTIMIZATION OF INTEGRATED MODEL

A. The economic structure of boiler combustion and denitration

The integrated cost mainly refers to the cost produced during the boiler combustion and denitration. In detail, the cost include coal consumption, reducing agent(ammonia) cost, sewage cost, power consumption for denitration and the electrovalent compensation[5]. The calculation is described in the following:

1) The coal consumption

The coal consumption of thermal power plants are effected by the equipment conditions. The relation between the change of boiler efficiency and coal consumption can be obtained. It can be described as in (8):

$$\Delta b = -\frac{\Delta \eta_{gl}}{\eta'_{gl}} \cdot b \qquad (8)$$

Δb is the change of net coal consumption which is due to the change of the boiler efficiency. $\Delta\eta_{gl}$ is the change of the boiler efficiency, η'_{gl} is the boiler efficiency after changed.

Based on the coal consumption b and the standard coal price P_{coal}（Chinese yuan /kg）, we can get the cost F_{coal} produced when the change of the boiler combustion efficiency affect the coal consumption in (9)

$$F_{coal} = (b + \Delta b) \times P_{coal} \qquad (9)$$

2) The consumption of ammonia (Chinese yuan/h)

During the denitration, the cost is mainly from the consumption of the reducing agent ammonia. In the paper [8], the author pointed out that the ammonia consumption could be calculated based on the gas flow, the emission concentration of the NOx in the boiler output, denitration efficiency. Formula (10) is as followed:

$$W_{NH_3} = \left(\frac{V_q \times C'_{NO} \times 17}{30 \times 10^6} + \frac{V_q \times C'_{NO_2} \times 17 \times 2}{46 \times 10^6}\right) \times NSRm \qquad (10)$$

W_{NH_3} is the reducing agent ammonia's hourly consumption (kg/h); V_q is the SCR gas flow in the air inlet port(Nm^3/h). C_{NO}、C_{NO_2} are the concentration of NO、NO_2 in the gas(mg/Nm^3). *NSRm* is the molar ratio of the ammonia-nitrogen equivalent. In the actual calculation, *NSRm* can be nearly relevant with the denitration efficiency. So that some certain ratio-calculation can be used to simplify the calculation, when the *NSRm* can replaced by the denitration efficiency[9].

Based on the consumption of the ammonia and the price of the ammonium hydroxide P_{NH_3}(Chinese Yuan/kg), the cost of the reducing agent ammonia F_{NH_3}（Chinese Yuan/h） can be obtained in (11).

$$F_{NH_3} = W_{NH_3} \times P_{NH_3} \qquad (11)$$

3) Sewage charge(Chinese Yuan/h)

The sewage charge refers to the fee charged by the government's environmental protection departments when there exist NOx in the thermal power plant emissions. The unit emission charging standard D_3（Chinese Yuan/kg）and total sewage charge F_3 can be calculated based on the denitration efficiency, gas flow, the emission concentration of the NOx in the boiler output and Chinese government effluent charge standard. The standard is as in (12). The 0.95 is the pollutional equivalent, and each equivalent will charge D_3.

$$\begin{aligned} F_3 &= D_3 \cdot V_q \cdot NOx_{out} \cdot 10^{-6} / 0.95 \\ &= D_3 \cdot V_q \cdot NOx_{in}(1 - \eta_{SCR}) \cdot 10^{-6} / 0.95 \end{aligned} \qquad (12)$$

4) Denitration electricity consumption （Chinese Yuan/h）

The SCR denitrification system will cost electricity during the process. The denitration electricity consumption F_4 can be got based on the following steps: First, to linear fit the connection between the ammonia spraying and the total current I. Then, the connection among the F_4, I and electricity price D_2(Chinese yuan/kw·h) can be described. In most cases, the larger the ammonia spraying, the more electricity the equipment cost. In the formula, the k and b are constant, by the data-fitting in (13) and (14)

$$I = k \cdot W_{NH3} + b \qquad (13)$$

$$F_4 = 1.732 \times 6000 \times I \times 0.83 \times D_2 / 1000 \qquad (14)$$

5) Valence compensation（Chinese Yuan/kwh）

Due to the rule of the valence compensation, the enterprises could get the valence compensation if the environmental policies are satisfied. Each KWh could get the compensation F_5[10,11].

6) Comprehensive cost of boiler combustion and denitration

The integrated cost of boiler combustion and denitrationt (CCBCD) is the sum value of all the cost referred in the above. What the destination of the optimization work is to minimize the CCBCD. And the integrated cost F of the unit power generation can be expressed by making the CCBCD divided by the electricity production, as in (15):

$$F = F_{coal} + \frac{F_{NH_3} + F_3 + F_4}{LOAD} - F_5 \qquad (15)$$

B. *The economic optimization example of the* integrated *model*

This article used the genetic algorithm to optimize the integrated model in different working conditions. Under the requirements of emissions and safety, the integrated cost F is set to be the optimized objective function. This function is designed to find the off-line optimal value under different working conditions, which means that the integrated cost can achieve the minimum value. Indeed, what remains to be explained that this optimization scheme is a kind of optimization with constraints. The safety of the boiler and the SCR need to be accounted within the prescribed scope, and also as the ammonia escape, denitration efficiency and exhaust gas temperature.

This optimization can be described in (16), f_1 is the connection between the manipulated variables and the characteristic variables. And f_2 stands for the integrated economy model of boiler combustion and denitrationt integrated system. [MV]min and [MV]max are the variation range of the manipulated variables. $(NOx_{out})_c$ is the permitted maxium emission. $(\eta_{SCR})_c$ is the minimal value of the denitration efficiency，$(\gamma_a)_c$ is max constraint of the ammonia escape.

$$\begin{aligned}
&NOx_{in}, \eta_{gl}, \eta_{scr} = f_1(DV, MV) \\
&F = \min f_2(NOx_{in}, \eta_{gl}, \eta_{scr}, W_{NH_3}) \\
&[MV]_{\min} \le MV \le [MV]_{\max} \\
&NOx_{out} \le (NOx_{out})_c \\
&[T_p]_{\min} \le T_p \le [T_p]_{\max} \\
&\eta_{SCR} \ge (\eta_{SCR})_c \\
&\gamma_a \le (\gamma_a)_c
\end{aligned} \qquad (16)$$

The ultra low emission standard $(NOx_{out})_c$ is valued for 50mg/m^3, T_p is controlled between 290 and 390℃. SCR denitration efficiency is no fewer 70%. The ammonia escape is controlled under 3ppm. Moreover, the ammonia spraying is used as the regulating variable. In order to make the *NOx* in *SCR* output not excessive and there are not too much ammonia escape, the top and bottom limitation need to found out based on the theoretical formula in (10).

But the cost of the coal consumption has taken a large proportion in the total cost. In some working conditions, in order to reduce the integrated cost and increase the boiler efficiency, the NOx in the boiler output will increase and so as the ammonia spraying. So that the cost of SCR denitration will increase. In this case, the safety and cost-effectiveness need further optimized.

This paper has improved the optimizing objective function, which aims at raising boiler efficiency and reducing the NOx in the boiler output. In the (17), λ_1, λ_2 separately are the concern extent coefficients(degree of concern) of the boiler efficiency and NOx concentration in the boiler output. These coefficients can be adjusted under the different economics and environmental policies.

$$\min f_1(DV, MV) = \lambda_1(1-\eta_{gl}) + \lambda_2 \cdot NOx_{in} \qquad (17)$$

The optimization steps are expressed in the following, to combine the solutions of minimal integrated cost and improved optimization method:

S1：For a certain working objective function, it is optimized by the (16) and the optimum value of the function is retained.

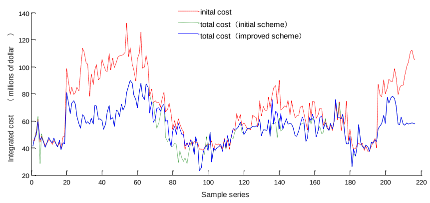
S2: Compare the denitration cost F_{SCR} before and after the optimization. If the cost is reduced, than S3 will be carried out, otherwise the S4 will be choosen.

S3: The optimization is effective and will be retained.

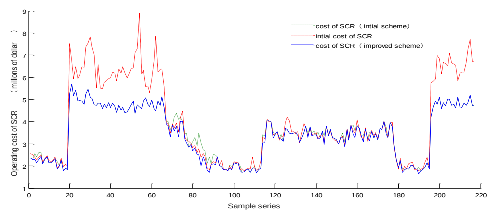
S4：By optimizing the objective function in (17), the optimized parameters will be achieved to calculate the units integrated cost F and the denitration cost F_{SCR}. And then the optimized result is retained.

The genetic algorithm is applied to optimize the problem. Firstly, the manipulated variables in different working points are off-line optimized to find the off-line optimum value. Secondly, the real-number encoding, adaptive mutation rate, the optimization reserved strategy are adopted to optimize the comprehensive economic model. For the chosen data, the parameter in genetic algorithm are set as M (population quantity)=80, T(evolutional generation)=100, pc(crossover rate)=0.6, pm0(initial mutation rates)=0.05.

This paper assumed that the unit has 5000 working hours (70% of the full load). The compared result of total cost and SCR denitration cost are separately showed in Fig. 5 before and after the optimization.



a) The total cost before and after optimization



b) The SCR denitration operating cost before and after optimization

Figure 5. The economic before and after the optimization in new method

From the optimization result, the total cost is reduced by 28.92% by using the improved method, and the SCR operating cost is also reduce by 14.37%. Moreover, the ammonia consumption is decreased from 179.6kg/h to 159.8kg/h. Otherwise, from the view of environment protection, as showed in Fig.6, the NOx in SCR output is decreased from 41.17mg/m3 to 35.43 mg/m3. After the optimization work, all the emissions are fewer than 50 mg/m^3 when the ultra-clean emissions are properly required. And then the boiler efficiency is increased by 0.215%. In conclusion, this paper has built a system of boiler combustion and denitration optimization which has great performance in economic and environmental benefits.

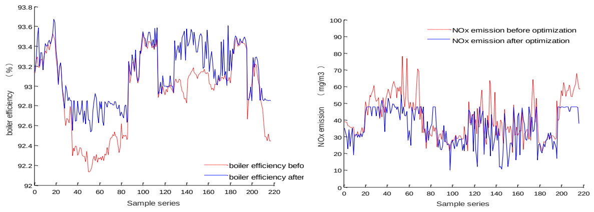


Figure.6. The contrast of environmental & economic before and after optimization

VI. CONCLUSION

By analyzing the mechanism of the boiler combustion and denitrification system, this paper has proposed the method to construct the integrated cost. The integrated cost mainly covers the coal consumption made from boiler combustion and the operation fee made by SCR denitration facilities. On the basis of LSSVM integrated model, this paper has used the GA algorithm of adaptive mutation rate to optimize different working conditions. In the constraint of standard emissions and safety, the total cost **F** is designed as the object function. The off-line optimum values are wanted to achieve the minimal total cost. Meanwhile, the problem of increasing SCR operating cost in this method is also made some improvement. In detail, the NOx emissions in the boiler output is reduced properly while the boiler efficiency is ensured, which finally achieve fewer ammonia spraying and lower SCR operating cost. From the optimizing results, the improved method has achieved making the total cost 29.82% fallen. And the ammonia has decreased 19.8kg/h, and the optimized emissions are lower than 50 mg/m^3. In general, the method can perform well in environmental and economic.

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