Research on Optimization of Emission Reduction Scheme for Thermal Power Based on Linear Programming

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Abstract. Coal-fired thermal power units emit a large amount of air pollutants, which has aggravated air pollution in China and seriously affected people's life and health. Therefore, it is necessary to formulate more reasonable emission reduction plans for thermal power units in China, so as to reduce air pollution. In order to maximize the comprehensive benefit of thermal power emission reduction, this paper put forward a method of optimizing the emission reduction scheme of thermal power units based on linear programming, and calculated the emission reductions in future.

1. Introduction

The thermal power industry has been a key point to deal with traditional environmental problems such as haze and acid rain pollution because of the large amount of pollutants such as dust, sulfur dioxide and nitrogen oxides emitted from the thermal power units[1-3]. In 2018, coal consumption in the thermal power industry reached 2.12 billion tons, accounting for 53.9 percent of China's total coal consumption. Emissions of sulfur dioxide, nitrogen oxide and dust were about 1.08 million tons, 1.03 million tons and 0.25 million tons respectively, accounting for about 15%, 9% and 4% of China’s total emissions of sulfur dioxide, nitrogen oxide and dust. Also, as an elevated source of pollutants, the thermal power units have long-distance transmission characteristics. In order to effectively control the emission of the thermal power industry, the relevant government departments in China have taken a series of important measures. As a result, the power industry emission reduction has achieved significant effects, especially after the Government Work Report in March 2015, which said to promote the ultra-low emissions of coal-fired power plants.

As to emission reduction in thermal power industry, many scholars have studied. Wenbo Xue et al studied the potential emission reduction of coal-fired power plants and the PM2.5 emission reduction efficiency in China’s Yangtze River Delta and Beijing-Tianjin-Hebei region [4]. Fahua Zhu et al proposed the technology integration of dust control, SO₂ control and NOₓ control for the ultra-low emission of air pollutants in coal-fired power plants [5]. Peishan Song et al collected 12 typical technology combinations for ultra-low-emission reformation of coal-fired units of 300MW and above in Guangdong province, calculated the cost and benefit of each technology, and plotted the cost-benefit curve of ultra-low-emission reformation [6]. At present, the technology of ultra-low emission reformation of thermal power unit is mature, but there is still a lack of relevant research on how to arrange the reduction scheme of thermal power unit to realize the social comprehensive benefit. In order to maximize the comprehensive benefit of thermal power emission reduction, this paper puts
forward a method of optimizing the emission reduction scheme of thermal power units based on linear programming by using the GAMS model.

2. Technical route of thermal power emission reduction
Due to various factors such as specific equipment selection, technical means of power generation, operating conditions, working conditions and operating life of each power plant, there are great differences in the specific technical routes adopted in implementing ultra-low emission retrofits, resulting in large differences in investment and operating costs. In this paper, the following three typical retrofit technical schemes are used for analysis.

2.1. Technical solution A
Technical solution A takes low and low temperature electrostatic precipitator technology (ESP) as the core. On the basis of low and low temperature electrostatic precipitator, the synergistic relationship between the precipitator system, the desulfurization system and the denitrification system is considered comprehensively. Each unit removes its main target pollutants, at the same time, the other pollutants are removed cooperatively or favorable conditions are created for the downstream units to remove the pollutants.

The main technical route implementation plan is as follows: flue gas denitrification device (SCR) → flue gas heat exchange device (FGC) → low-low-temperature electrostatic precipitator → limestone-gypsum wet FGD system with high desulfurization and dedusting efficiency (WFGD) → flue gas reheat device (FGR, optional installation).

2.2. Technical solution B
Technical solution B takes the wet electrostatic precipitator (WESP) technology as the core. Wet electrostatic precipitator, as a technical equipment for fine treatment of pollutants in coal-fired power plants, is generally used in conjunction with dry ESP and wet desulfurization system, and can also be combined with low and low temperature ESP, which can be applied to new projects and reformation projects. The main technical route includes denitrification device, electrostatic precipitator, wet desulfurization device and wet electrostatic precipitator. The flue gas enters the chimney from the wet electrostatic precipitator.

2.3. Technical solution C
Technical solution C takes the electric bag technology as the core. Because of its unique dedusting mechanism, the electric bag composite dust collector has the advantages of long-term, stable and low emission. The adaptability of coal species is strong, which can guarantee the dust collector's export under 20mg/m³. In order to achieve the requirements of ultra-low emissions, the electric bag composite dust collector can be optimized and upgraded, and corresponding measures must be matched. Currently, the following typical technical route implementation is available.

Ultra clean electric bag + super clean desulfurization tower. The dust collector outlet is not directly connected to the chimney, but also through the desulfurization tower. Therefore, the desulfurization tower dedusting desulfurization, mist removal efficiency directly affect the export emissions. The use of ultra-clean electric bag composite dust collector, to achieve the dust outlet <1mg/m³. By adopting the process of ultra clean electric bag + super clean desulfurization tower, wet electrostatic precipitator can be eliminated, saving investment and reducing operation and maintenance costs.

3. Optimization model
The relevant emission reduction measures have been introduced in the previous chapter. Each method has its own cost and benefit, this paper presents a cost-benefit method for thermal power plant of different capacity, providing advice on which technical solution to use for different units.
3.1. Objective function
The objective of the optimization model is to maximize the total comprehensive benefits. The objective function is expressed as:

$$\max Z = W^T X$$

(1)

In the formula, $Z$ stands for total comprehensive benefits. $X$ is a matrix, which stands for the capacity of thermal power units for different capacity types and different technical solutions. $W$ is also a matrix, which stands for the reformation benefit of thermal power units for different capacity types and different technical solutions.

$$W = B - C$$

(2)

In the formula, $B$ represents the income reformation will bring, which includes the direct income and indirect income. $C$ represents the reformation cost which includes investment cost and maintenance cost.

3.2. Primary Constraints
The reformation capacity constraints:

$$0 \leq X_{i,j,k}$$

(3)

$$0 \leq \sum_{i=1}^{M} \sum_{j=1}^{N} X_{i,j,k} \leq Ins_k$$

(4)

Emission reduction constraints:

$$0 \leq \sum_{j=1}^{P} \sum_{k=1}^{N} \left( t_{i,j,k} \ * X_{i,j,k} \right) \leq E_i$$

(5)

In the above inequalities, $i$ stands for different pollutant, $j$ stands for different technical solution, and $k$ stands for thermal power units of different capacity, $X_{i,j,k}$ stands for the reformation capacity for a certain type of thermal power unit ($k$) with the technology ($j$) used to reduce a certain pollutant ($i$), $Ins_k$ is the total capacity of a certain type of thermal power unit in future year, $t_{i,j,k}$ represents the emission performance, and $E_i$ is the emission reduction of a certain type of pollutant.

4. Optimization method
According to the above objective function and constraints, an optimization model for thermal power units emission reduction is established. The linear programming algorithm is used to determine the thermal power units emission reduction scheme which has the optimal comprehensive benefit. The specific steps are as follows.

First, determine the initial feasible base matrix $B_o$ and the feasible basis variable group $X_{B_o}$ according to the standard type of the linear programming problem. Calculate the inverse matrix $B_o^{-1}$ of $B_o$ and find the initial solution.

$$\begin{bmatrix} X_{B_o} \\ X_{N_o} \end{bmatrix} = \begin{bmatrix} B_o^{-1} b_o \\ 0 \end{bmatrix}$$

(6)
Find the initial objective function value.

\[ Z = C^T_{B_0} B_0^{-1} b_0 \]  
(7)

\[ Y_0^T = C^T_{B_0} B_0^{-1} \]  
(8)

\[ b_1 = B_0^{-1} b_0 \]  
(9)

Second, calculate the test number vector of the non-base variable group.

\[ \sigma^T_{N_0} = C^T_{N_0} - C^T_{B_0} \]  
(10)

\[ B_0^{-1} N_0 = C^T_{N_0} - Y_0^T N_0 \]  
(11)

If \( \sigma^T_{N_0} \leq 0 \), the function gets the optimal solution and stops the operation. If \( \sigma_j > 0 \), \( j \) is the number of the non-base variable, then go to the next step.

Third, according to the non-base variable corresponding to \( \text{max} \{ \sigma_j \mid \sigma_j > 0 \} = \sigma_k \), determine \( x_k \) as the base variable. Calculate \( B^{-1} P_k \) at the same time. If \( B^{-1} P_k \leq 0 \), there is no solution to the linear programming problem and stop the calculation. Otherwise, go to the next step.

Last, according to the \( \theta \) principle.

\[ \theta = \min_i \left\{ \frac{(B^{-1} b)_i}{(B^{-1} P_k)_i} \mid (B^{-1} P_k)_i > 0 \right\} = \frac{(B^{-1} b)_i}{(B^{-1} P_k)_i} \]  
(12)

Its corresponding base variable is \( x_j \), and it is determined that \( x_j \) is an off-base variable. If \( x_k \) is the base variable and \( x_j \) is the off-base variable, then \( a_{jk} \) will be the pivot of the new round of reformation.

Then a new set of feasible base variables \( X_{B_1} \) and a new set of feasible base matrix \( B_1 \) can be obtained. Then, calculate the inverse matrix \( B_1^{-1} \) of the new feasible basis matrix \( B_1 \).

\[ b_2 = B_1^{-1} b_1 \]  
(13)

\[ Z = C^T_{B_1} B_1^{-1} b_1 \]  
(14)

\[ Y_1^T = C^T_{B_1} B_1^{-1} \]  
(15)

5. Empirical research

5.1. Power structure setting

With the increasingly severe constraints of climate and environment, the pace of power structure adjustment in China is accelerating, and the space for thermal power development is narrowed. In the future, thermal power units will mainly be large efficient and environmental. According to the 13th Five-Year Plan of China Electric Power Development, the installed coal-fired power capacity should be controlled within 1.1 billion kilowatts in 2020. Some experts predict that the installed coal power capacity will peak around 2025, with a peak of about 1.2 billion kilowatts. However, considering the
decommissioning time, it is expected that the coal power installed in 2030 will be basically the same or slightly lower than that in 2020. According to this estimate, the installed coal power capacity in 2020 and 2030 will be 1.1 billion kW and 1.08 billion kW respectively. The coal-fired power structure in 2020 and 2030 is shown in Table 1.

| Time     | 0.6-10 | 10-20 | 20-30 | 30-60 | 60-100 | ≥100 | Total |
|----------|--------|-------|-------|-------|--------|------|-------|
| 2020     | 6900   | 6400  | 5400  | 34600 | 43000  | 13700| 110000|
| 2030     | 3900   | 4200  | 3000  | 30000 | 49900  | 17000| 108000|

5.2. Optimization Results

(1) Emissions of different pollutants

In terms of emission reduction effect, the emission of dust, sulfur dioxide and nitrogen oxide in the thermal power industry will be 137,000 tons, 785,000 tons and 872,000 tons respectively in 2020, 45%, 27% and 15% lower than that in 2018. In 2030, the emissions of soot, sulfur dioxide and nitrogen oxide in the thermal power industry were 39,000 tons, 271,000 tons, 398,000 tons and 232,000 tons, respectively, 84 percent, 75 percent and 61 percent lower than those in 2018. Emission of different pollutants in 2020 and 2030 are shown in Figure 1.

(2) Application of technical solution

From the perspective of the application of different technical solutions, in 2020, technical solution A and technical solution B will be mainly adopted, and the capacity of the applied units will account for about 78% of the total qualified units. Due to the high cost and certain limitations in the application of filter material, technical solution C will be mainly applied to units with capacity of more than 600,000 Kw. The application of different technical solutions in 2020 is shown in Figure 2.
In 2030, the technical solution C will be gradually mature, and the investment and operating cost will be also greatly reduced, which will be applied in parallel with technical solution A and technical solution B. The application of different technical solutions in 2020 is shown in Figure 3.

![Figure 3. Application of different technical solutions in 2030.](image)

6. Conclusions

During the 13th five-year plan period, the thermal power industry still has some space for conventional pollutant emission reduction, but after 2020, the space for emission reduction will gradually be saturated, and after 2030, within the framework of existing mechanisms, policies and technical conditions, the space for emission reduction is close to the upper limit.

Before 2020, the flue gas treatment technology route with low-temperature electric dust removal as the core and wet electric dust removal as the core are the most cost-effective, and the ultra-low emission technology route should mainly choose low-temperature electric dust removal technical solution and wet electric dust removal technical solution. After 2020, the flue gas treatment technology with electric bag technology as the core will be gradually mature. By 2030, the flue gas treatment technology line taking the electric bag technology as the core of will be the most cost-effective, its application capacity will be more than the wet dust removal technical solution, only second to the low-temperature dust removal technical solution.

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