Calculation and Analysis of Energy Consumption Index of Environmental Protection Facilities in Coal-fired Power Plant

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Abstract. Energy consumption of environmental protection facilities in coal-fired power plants is an important part of energy consumption of generating units. Taking 2 x 600 MW generating unit as an example, in this paper discusses the Energy Consumption Index Composition and Calculation Method of Environmental Protection Facilities. The results show that the energy consumption index for removal of unit quality pollutants can better reflect the energy consumption level of environmental protection facilities. The fan electricity consumption caused by resistance of environmental protection facilities is an important part of energy consumption. The calculation results can provide basic data and basis for energy consumption management and energy efficiency improvement of environmental protection facilities of coal-fired units.

1. Introduction
With the development of power system, the capacity of hydropower, nuclear power and wind turbine assemblies is increasing all over the country. However, the energy pattern dominated by coal has not changed [1]. Thermal power will continue to dominate for a long time. Energy saving and emission reduction has become an inevitable choice for the sustainable development of the power industry [2]. The “Twelfth Five-Year Plan” and "Thirteenth Five-Year Plan" promulgated by the state have elevated energy conservation and emission reduction to a major strategic task for China's economic and social development. The power generation industry has become the focus of the implementation of the national policy of energy conservation and emission reduction, consumption reduction and efficiency enhancement. With the implementation of various national energy-saving and emission reduction policies, the emission control effect of smoke and sulfur dioxide in thermal power plants are obvious. However, the large-scale operation of environmental protection facilities has led to a sharp rise in energy consumption of auxiliary power. According to statistics, the electricity consumption of desulfurization system accounts for about 1.0-1.6% [3] of the generation capacity of power plant, which leads to a 3-6 g/kwh increase in power supply coal consumption of power plant.

At this stage, power generation enterprises should not only meet increasingly stringent environmental emission requirements, but also keep up with the national energy-saving trend and reduce energy consumption in operation. In order to meet the national emission reduction requirements, energy-saving optimization of facilities must be considered, and all of these require power generation enterprises to understand the level of energy consumption of equipment.

This paper takes a coal-fired power plant 2x600 MW unit as the research object, takes a single environmental protection facility as the foothold, introduces the composition of energy consumption index of environmental protection facility in power generation enterprise, and obtains the energy
consumption level of environmental protection facility by calculating typical index, which provides reference for comparing energy consumption index of environmental protection facility among units, and provides basic data and the direction of guidance for upgrading and optimizing adjustment of environmental protection facility, has great practical significance.

2. Energy consumption index

2.1 Composition of energy consumption index

Environmental protection facilities in coal-fired power plants mainly include desulfurization devices, denitrification devices and dust collectors. The main energy consumption of desulfurization unit is electricity consumption, water consumption and reductant consumption. The main energy consumption of denitrification unit are electricity consumption and reductant consumption, and the main energy consumption of dust collector are electricity consumption. In addition, because the operation of environmental protection facilities is based on the flue gas flow, the fan electricity consumption which provides the flue gas flow energy is also an important part of energy consumption of environmental protection facilities.

In the design parameters of environmental protection facilities, the following performance index are generally given: limestone consumption per hour, water consumption and electricity consumption. This method can only evaluate the operation of environmental protection facilities when the design conditions are met. In the daily operation of units, limited by the load rate and fluctuation of units, the hourly energy consumption index cannot directly judge the operation level of environmental protection facilities, nor can it analyze the energy consumption level from a macro perspective. Therefore, in order to measure the level of energy consumption, the following two energy consumption index can be used: "energy consumption value per unit generation capacity " and "energy consumption value for removing pollutants per unit mass". By comparing with the same type of units, the potential points of energy saving can be analyzed, and targeted measures can be taken to improve efficiency of the operation level of facilities.

2.2 Calculating method of energy consumption index

The energy consumption per unit generation capacity is calculated as follows:

\[ E_f = \frac{B_x}{W_f} \]  

\( E_f \), the index value of energy consumption per unit generation capacity.  
\( B_x \), the statistical value of energy consumption, such as electricity consumption, water consumption, reductant consumption, etc.  
\( W_f \), the generation capacity of unit, unit kWh

The energy consumption value of removing pollutants per unit mass is calculated as follows:

\[ E_t = \frac{B_x}{Q_t} \]  

\( E_t \), the energy consumption index for removing pollutants per unit mass.  
\( B_x \), the statistical value of energy consumption, such as electricity consumption, water consumption, reductant consumption, etc.  
\( Q_t \), the amount of pollutants removed, unit kg.

3. Typical calculation cases of energy consumption index

3.1 Overview of units and environmental protection facilities

2x600 MW power plant units are equipped with H G-2008/18.2-YM2 boiler produced by Harbin Boiler Plant. The boilers are subcritical pressure, one intermediate reheating and forced circulation drum furnaces. The steam turbines are N630-16.7/538/538 units produced by Harbin Steam Turbine Plant, which are single-axis, intermediate reheating, four-cylinder, four-exhaust steam and condensing steam turbines.
Both of the two units are equipped with environmental protection facilities such as denitrification, dust collector and desulfurization, implement the “Air Pollutant Emission Standard for Thermal Power Plants” (GB13223-2011). On the basis of meeting the national standards, the ultra-low emission transformation was further completed in 2016. The emissions of smoke, SO$_2$ and NO$_X$ are less than 10 mg/m$^3$, 35 mg/m$^3$ and 50 mg/m$^3$, respectively. The environmental protection facilities are listed in Table 1.

| No. | Item                      | Type/Parameter                              |
|-----|---------------------------|---------------------------------------------|
| 1   | Denitrification device    | Type Selective catalytic reduction (SCR)    |
|     | Export NOx concentration, mg/m$^3$ | 50                                           |
| 2   | Dust collector            | Type Electric bag compound                  |
|     | Export dust concentration, mg/m$^3$ | 20                                           |
| 3   | Desulfurization device    | Type Limestone-gypsum wet process           |
|     | Export SO$_2$ concentration, mg/m$^3$ | 35                                           |
|     | Export dust concentration, mg/m$^3$ | 10                                           |
|     | Booster fan (Yes / No)    | No                                          |

3.2 Energy consumption calculation of desulfurization system

In this case, the domestic mainstream limestone-gypsum wet desulfurization process is adopted in the desulfurization system. The main energy consumption is electricity consumption, water consumption and limestone consumption. The three data are taken from the unit management account, include the monthly statistical tables of desulfurization water consumption, electricity consumption and limestone consumption. In addition, the generation capacity is taken from the monthly report of unit production, and the amount of SO$_2$ removed are taken from the CEMS report of environmental protection.

Table 2 shows the energy consumption index from 2015 to 2017. Since both of the two units were reformed for ultra-low emission in 2016, the data of 2016 are not included. Due to the existence of the public system in desulfurization, it is impossible to accurately obtain the electricity and water consumption of a single unit. For the convenience of analysis, the energy consumption index are considered by the whole plant.

| No. | Item                                             | Unit | 2015    | 2017    |
|-----|--------------------------------------------------|------|---------|---------|
| 1   | Limestone consumption                            | t    | 20748   | 15537   |
| 2   | Water consumption                                | m$^3$| 893864  | 826618  |
| 3   | Electricity consumption                          | kW·h | 43722001| 30657618|
| 4   | Generation capacity                              | $10^4$ kW·h | 832342 | 491752  |
| 5   | Amount of SO$_2$ removed                         | kg   | 10502655| 8023166 |
| 6   | Limestone consumption per unit generation capacity| g/kW·h | 2.493   | 3.160   |
| 7   | Water consumption per unit generation capacity   | $10^4$ m$^3$/kW·h | 1.074 | 1.681   |
| 8   | Power consumption rate of desulfurization        | %    | 0.525   | 0.623   |
| 9   | Ca/S                                             | -    | 1.138   | 1.115   |
| 10  | Water consumption for removing SO$_2$ per unit mass| m$^3$/kg | 0.085 | 0.103   |
| 11  | Electricity consumption for removing SO$_2$ per unit mass| kW·h/kg | 4.163 | 3.821   |
3.3 Energy consumption calculation of denitrification system

In this case, the denitrification system adopts the domestic mainstream SCR process, the main energy consumption is the consumption of reductant and electricity. The consumption data of reductant are obtained from the monthly statistical table, electricity consumption mainly comes from dilution fan, the generation capacity are taken from monthly report of unit production, and the amount of NOx removed are taken from CEMS report of environmental protection.

Table 3 shows the energy consumption index of 2015 and 2017. The electricity consumption of denitrification only includes the electricity consumption of the equipment in SCR area, but not ammonia area.

Table 3. Energy consumption statistics and index calculation results of denitrification system.

| No. | Item                              | Unit | 2015   | 2017   |
|-----|-----------------------------------|------|--------|--------|
| 1   | Reductant consumption             | t    | 1452   | 1550   |
| 2   | Electricity consumption           | kW·h | 259603 | 256595 |
| 3   | Generation capacity               | 10^4·kWh | 832342 | 491752 |
| 4   | Amount of NOx removed             | kg   | 7505164 | 760792 |
| 5   | Reductant consumption per unit generation capacity | g/kW·h | 0.174 | 0.315 |
| 6   | Power consumption rate of denitrification | % | 0.003 | 0.005 |
| 7   | Reductant consumption for removing NOx per unit mass | kg/kg | 0.193 | 0.204 |
| 8   | Electricity consumption for removing NOx per unit mass | kW·h/kg | 0.035 | 0.034 |

3.4 Energy consumption calculation of dust collector

In this case, the dust collector adopts the electric bag compound dust removal process, the main energy consumption is electricity consumption. The electricity consumption of the dust collector is taken from the operation log of the dust collector, generation capacity are taken from the monthly report of the unit production, and the amount of dust removed are taken from the coal quality analysis and the CEMS report.

Table 4 shows the energy consumption index of 2015 and 2017.

Table 4. Energy consumption statistics and index calculation results of dust collector.

| No. | Item                              | Unit    | 2015   | 2017   |
|-----|-----------------------------------|---------|--------|--------|
| 1   | Electricity consumption           | kW·h    | 8732229 | 4933460 |
| 2   | Generation capacity               | 10^4·kWh | 832342 | 491752 |
| 3   | Amount of dust removed            | kg      | 371213519 | 291468024 |
| 4   | Power consumption rate of dust collector | % | 0.105 | 0.100 |
| 5   | Electricity consumption for removing dust per unit mass | kW·h/kg | 0.024 | 0.017 |

3.5 Loss of fan electricity consumption caused by increased resistance of environmental protection facilities

Because the electricity consumption of environmental protection facilities is only the electricity consumption of the system self-equipment, the fan electricity consumption caused by the system resistance is not considered. The electricity consumption which the dust collector and denitrification system overcome the system resistance comes from the induced draft fan. The desulphurization system
which has cancelled the booster fan and integrated the induced draft fan and the booster fan, the power is also provided by the induced draft fan. For the unit which has accomplished the integration of the induced draft fan and the booster fan and cancelled the booster fan, can significantly reduce the plant electric power consumption rate of the desulfurization system.

Taking the increase of 100 Pa resistance in a single environmental protection facility system as an example, the influence of the increase of system resistance on electricity consumption is evaluated. The calculation method is as follows:

\[
P = \frac{Q \times p}{3600 \times 1000 \times \eta_1 \times \eta_0}
\]

\[
= \frac{2100000 \times 100}{3600 \times 1000 \times 0.85 \times 0.95}
\]

\[
= 72.2\text{ kW}
\]

\(P\), the increase of electricity consumption caused by the increase of fan output. 
\(Q\), the flue gas flow rate of induced draft fan at full load. In this case, it is \(210 \times 10^4\text{ m}^3/\text{h}\). 
\(p\), the increased output of the induced draft fan, this case is 100Pa. 
\(\eta_1\), the fan efficiency. In this case, it is 0.85. 
\(\eta_0\), the power factor of the fan motor. In this case, it is 0.95.

From the above formula that the direct electricity consumption of the fan increases 72.2 kW when the pressure head of the fan is increased by 100 Pa. For the units with improper design or poor operation and maintenance, the resistance of environmental protection facilities often increases by more than 600 Pa. Taking the increase of 600 Pa as an example, the increase of electricity consumption of fan is 433 kW, which is equivalent to a desulfurization slurry circulating pump. The annual cost increases by hundreds of thousands of Yuan, and the impact on electricity consumption of desulfurization plant cannot be ignored. In addition, the increase of resistance will easily lead to insufficient fan output, which will force the boiler to operate at reduced load and the economic efficiency of the unit will be further reduced.

4. Calculation and analysis

4.1 Analysis of calculation method
The calculation of energy consumption index of environmental protection facilities involves the statistics of daily data, the accuracy of calculation results depends on the accuracy of data sources, electricity consumption, water consumption and reductant consumption can be obtained by measuring tools, and the generation capacity of unit is obtained through power meters. Therefore, the energy consumption per unit of power generation can obtain more accurate results.

The energy consumption value of de-pollution per unit mass needs to obtain the removal amount of flue gas pollutants, mainly involving \(SO_2\), \(NO_x\) and dust. There are usually three algorithms for pollutant removal: CEMS real-time monitoring method, material balance algorithm, production and emission coefficient method [4]. The real-time monitoring method of CEMS is obtained by calculating the product of the difference in raw and net flue gas concentration and the product of the flue gas flow monitored by CEMS, and the results are accurate. The material balance algorithm is obtained by material accounting of coal components when the raw flue gas concentration cannot be obtained by monitoring in real time, and through the removal efficiency or the measured values of net flue gas concentration to obtain the amount of pollution removal. The production and emission coefficient method is that when the raw net flue gas concentration cannot be obtained by real-time monitoring, by using the method of production and emission coefficient and the calculation of pollutant production and emissions in combination with fuel consumption.

In this case, the raw and net flue gas \(SO_2\) concentrations and \(NO_x\) concentrations can be monitored in real time. Therefore, the CEMS real-time monitoring method is preferred for \(SO_2\) and \(NO_x\) removal.
For the amount of the dust removal, because the gas concentration cannot be monitored at the outlet of boiler hearth in real time, therefore the raw and net flue gas concentration can be calculated by material balance calculation, and the total outlet of the flue gas concentration can be used for the net flue gas dust concentration.

For units using in-furnace calcium injection desulfurization process, because the SO$_2$ concentration of raw flue gas cannot be monitored in real time, the material balance algorithm method is adopted; For units using SNCR denitrification process, because the raw flue gas NO$_x$ concentration cannot be monitored in real time and cannot be accurately calculated through coal species, the emission coefficient method is adopted; In addition, for small capacity units that do not have CEMS, the calculation of energy consumption index needs to adopt the production and emission coefficient method.

When comparing the energy consumption index between units, if the coal as fired is the same or similar, both of the energy consumption index per unit power generation and the energy consumption index for removing pollutants per unit mass can be adopted. If the type of coal as fired is different, it is not recommended to use the energy consumption index of unit power generation to compare. Taking the electricity consumption of desulfurization system as an example, the electricity consumption is closely related to the amount of SO$_2$ removal. With the decrease or increase of SO$_2$ concentration in the raw flue gas, it is necessary to stop and put in a slurry circulating pump to prevent flue gas pollutant concentration exceeding the standard [5]. Therefore, desulfurization electricity consumption is directly related to coal sulfur content, while coal sulfur content is not directly related to generation capacity. It can be said that coal quality is the key factor affecting the energy consumption index of environmental protection equipment. When comparing the energy consumption among units with large differences in coal types, it is more appropriate to adopt the energy consumption index of removing pollutants per unit mass.

4.2 Analysis of calculation results

The electricity consumption rate and Ca/S ratio of desulfurization system are two key index for desulfurization system. In this case, the electricity consumption rate of desulfurization is less than 0.7%, which is lower than the conventional value (1%). The reason is that the unit has been integrated of the induction draft and the booster fan. The ratio of calcium to sulphur is about 1.03 in general design, but it is 1.14 in this case, which indicates that the utilization rate of limestone is not high and should be paid more attention as a point of consumption reduction. For desulfurization water consumption, the water loss is mainly due to the evaporation of water vapor being carried away by the net flue gas and condensed in the flue, so it should be recycled.

The consumption of reductant for removing NO$_x$ per unit mass is a key energy consumption index in denitrification system. The uniformity of ammonia-nitrogen molar ratio at the inlet can be improved by ammonia spraying optimization adjustment test.

Electricity consumption is an important energy consumption index of ESP and electric bag dust collector. In this case, the electricity consumption rate of ESP is 0.1%. For the bag dust removal process, it should pay attention to the resistance of dust collector. The energy consumption is mainly reflected in the loss of electricity consumption caused by the increase of fan output.

From the point of view of electricity consumption of the environmental protection facilities, desulfurization system accounts for the largest proportion, followed by dust collector, and denitrification system is the smallest. The focus should be on reducing the electricity consumption in desulfurization and the operation mode of desulfurization system should be optimized.

5. Conclusion

(1) The increase of fan electricity consumption caused by the increase of system resistance of environmental protection facilities accounts for a large proportion of energy consumption, which cannot be ignored in calculation.

(2) When calculating the energy consumption index of pollutant removal per unit mass, the CEMS
real-time monitoring method should be preferred in order to select the accurate calculation method of monthly pollutant emission reduction from data sources, so as to ensure that the calculation results can truly reflect the energy consumption level of environmental protection facilities.

(3) The energy consumption index of unit power generation can be obtained directly from the data source, so the calculation results are accurate. It can be used to compare the energy consumption index between units with similar coal as fired, and can intuitively reflect the overall operation status and energy consumption level of environmental protection facilities.

(4) The energy consumption value of removing pollutants per unit mass is more suitable for energy consumption comparison between units with large difference in the type of coal as fired.

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