Research on Carbon Emission Index Data of Turbine Unit Based On Variable Parameter Operation

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Abstract. At present, the problem of climate warming caused by greenhouse gases dominated by CO2 has become the focus of global environmental governance, and China is facing severe pressure of carbon emission reduction internationally. In this paper, from the perspective of the operation of coal-fired units, based on the CO2 generation coefficient of unit standard coal consumption, combined with the consumption difference analysis, the influence degree of the main controllable operating parameters such as the pressure, temperature of superheated steam and reheated steam of the units, as well as the boiler exhaust temperature, on \( Q_{\text{co2}} \), that is, the sensitivity of \( Q_{\text{co2}} \) to the changes of each parameter is studied. On-site operating personnel of the unit can focus on monitoring and real-time adjustment of controllable operating parameters that have a great impact on \( Q_{\text{co2}} \), so as to ensure that the unit is at a low carbon emission intensity level, thus reducing the total carbon emissions of coal-fired power plants. Finally, through experiments, it is proved that the steam turbine parameter optimization method studied in this paper can provide higher unit efficiency and reduce carbon emission level.

1. Introduction
The carbon emission of coal-fired power plants in the power industry is huge, which is one of the key targets for carbon emission reduction [1]. The European Union and other developed regions have started to adopt carbon emission trading mechanism to encourage high-carbon enterprises to take the initiative in carbon emission reduction. China is gradually establishing a sound carbon trading market and relevant legal mechanisms to explore the formulation of carbon tax policies [2]. From January 1, 2020, the power sector cancels the linkage mechanism of coal and power generation and benchmark electricity price, realizes full marketization of coal and power price, and specifies that the industrial electricity price will only fall but not rise [3]. The coal-fired power market-oriented reform and the coming carbon emission charging policy will undoubtedly further increase the production cost of coal-fired power plants [4]. In general, reducing the carbon emission intensity of coal-fired power plants is not only an urgent requirement for China to reduce CO2 emissions and develop a low-carbon economy, but also an important way to reduce the cost of coal power [5].

Carbon intensity of coal-fired power supply \( Q_{\text{co2}} \), (i.e. the carbon emission generated in the coal-fired process under the unit power supply, g / (kW · h)) accounts for about 98% of the total carbon emission intensity of the coal-fired power plant, and is largely affected by the operation level of the unit, which is the key object and main breakthrough point of carbon emission reduction.
2. Thinking of carbon sensitivity analysis
The coal-fired power generation system can be regarded as a comprehensive system composed of several subsystems, such as boiler, pipeline and steam turbine system. Each subsystem has corresponding system efficiency. When the efficiency of corresponding subsystem changes due to the change of a certain operating parameter of the unit, the total efficiency of the system will change, thus the coal consumption and $Q_{co2}$ of power supply of the unit will also change. In other words, the change of operating parameters affects $Q_{co2}$ by changing the total efficiency of the system [6]. Therefore, when studying the sensitivity of $Q_{co2}$ to the changes of various operating parameters, two layers of relationship can be studied step by step.

The first step is to analyze the change law of $Q_{co2}$ when the total efficiency of the system changes, and then get the relationship between the change of the efficiency of each subsystem and the change of $Q_{co2}$ according to the change law of the total efficiency of each subsystem;

In the second step, based on the consumption difference analysis, the relationship between the variation of specific operating parameters and the efficiency change of corresponding subsystems is studied. Combining the two-layer relationship obtained from the above steps, the calculation Eq. between the variation of operating parameters and the variation of $Q_{co2}$ can be obtained, that is, the carbon sensitivity calculation model [7]

The determination of the first-layer relationship needs to be based on the quantitative relations among $Q_{co2}$, the total efficiency of the system and the efficiency of each subsystem. Concept of CO2 generation coefficient $T$ for unit standard coal consumption is:

$$T = \lambda_m \times \theta_m \times \frac{44}{12}$$  \hspace{1cm} (1)

In Eq. 1, $\lambda_m$ is the mass fraction of unit standard coal consumption, which can be obtained by converting the mass fraction of actual coal burning; $\theta_m$ is the carbon oxidation rate, and $\frac{44}{12}$ is the degree of complete combustion of carbon in the boiler [8].

$T$ reveals the linear relationship between the power supply coal consumption of coal-fired units and $Q_{co2}$. The power supply coal consumption $d_{cp,n}$ can be calculated according to Eq. (2):

$$d_{cp,n} = \sqrt{122.8 \mu_p \left(1 - \eta_{cp} \right)}$$  \hspace{1cm} (2)

$$\mu_{cp} = \mu_b \times \mu_p \times \mu_t \times \mu_m \times \mu_g$$  \hspace{1cm} (3)

In Eq. 2, 3, $\eta_{cp}$ is the power consumption rate of the plant; $\mu_{cp}$ is the total efficiency of the system; $\mu_b, \mu_p, \mu_t, \mu_m, \mu_g$ are boiler efficiency, pipe efficiency, absolute internal efficiency of steam turbine, mechanical efficiency and generator efficiency [9].

After $T$ and $d_{cp,n}$ are obtained, carbon emission intensity $Q_{co2}$ of coal power supply is:

$$Q_{co2} = T \cdot \sqrt{122.8 \mu_{cp} \left(1 - \eta_{cp} \right)}$$  \hspace{1cm} (4)

Eq. (3) and Eq. (4) show the quantitative relationship between the efficiency of $Q_{co2}$, $\mu_{cp}$ and each subsystem. When other indexes remain unchanged, the variation of carbon emission intensity of coal-fired power supply $\nabla Q_{co2}$ can be calculated from Eq. (5):
In Eq. 5, \( \phi \mu_p \) is the relative change of the total efficiency of the system; \( Q'_{\text{co}_2} \) represents the changed indicator and parameter.

It can be seen from Eq. (5) that the variation trend of \( Q_{\text{co}_2} \) and \( \mu_p \) is opposite, and the higher \( \mu_p \), the smaller \( Q_{\text{co}_2} \) is [10].

The efficiency of each subsystem of a coal-fired power unit can be regarded as a set of variables that are independent from each other and linearly independent. When the efficiency of a single subsystem changes while the efficiency of other subsystems remains unchanged, according to mathematical deduction, the relative change of the efficiency of a single subsystem is the same as \( \phi \mu_p \), namely:

\[
\phi \mu_p = \phi \mu_b = \phi \mu_i = \phi \mu_m = \phi \mu_g
\]  

(6)

By substituting Eq. (6) into Eq. (5), the general calculation model between the relative change of efficiency of each subsystem and the change of \( Q_{\text{co}_2} \) can be obtained:

\[
\nabla Q_{\text{co}_2} = Q_{\text{co}_2} \cdot \phi \mu
\]  

(7)

In Eq. 7, \( \phi \mu \) is the relative change of efficiency of any subsystem.

It can be seen from Eq. (7) that, when a change in an operating parameter causes a change in the efficiency of the corresponding subsystem, the relative change in the efficiency of the subsystem has a linear relationship with \( \nabla Q_{\text{co}_2} \), and the proportional coefficient is \( Q_{\text{co}_2} \). The absolute value of \( \nabla Q_{\text{co}_2} \) reflects the high or low carbon sensitivity of the operating parameter, and the positive and negative values indicate that the change in the operating parameter makes \( Q_{\text{co}_2} \) decrease or increase.

3. Carbon sensitivity calculation model

Unit operation parameters are divided into controllable operation parameters and uncontrollable operation parameters. From the perspective of unit operation, the author studies carbon emission reduction measures and selects the main controllable operating parameters that can be adjusted by field operators to conduct carbon sensitivity analysis. Boiler efficiency, absolute internal efficiency of steam turbine and auxiliary power rate has the greatest impact on carbon emission intensity of coal-fired power supply. According to the idea of carbon sensitivity analysis, the carbon sensitivity calculation model can be established for the main controllable operation parameters that affect the efficiency of the first two systems. In order to directly show the impact of the change of auxiliary power rate on \( Q_{\text{co}_2} \), the carbon sensitivity calculation model is established by selecting the auxiliary power consumption.

3.1. Calculation model of boiler side parameter carbon sensitivity

Among the energy losses of the boiler system, the exhaust heat loss R2 and the incomplete solid combustion heat loss R4 are large and can be adjusted from the operation aspect. The controllable operation parameters affecting R2 and R4 are respectively the boiler exhaust temperature \( c_p \) (°C), the exhaust oxygen volume fraction \( \omega O_2 \) (%) (hereinafter referred to as the exhaust oxygen content) and the carbon content \( \omega f_h \) (%) of fly ash.

When \( c_p \) changes and other parameters remain unchanged, \( \nabla Q_{\text{co}_2} \) is:

\[
\nabla Q_{\text{co}_2} = Q_{\text{co}_2} \cdot \phi \mu_b (c_p)
\]  

(8)
In Eq. 8, $\phi \mu_b (c_{py})$ is the relative change of boiler efficiency caused by $c_{py}$ change; $V_{gy}$ and $V_{H_2O}$ are the actual volume of dry flue gas and water vapor produced by fuel combustion of 1kg, m$^3$/kg respectively. $c_{py}$ and $c_{pyC}$ are the average specific heat capacity of dry flue gas and water vapor at constant pressure, kJ/(kg•K); $J_r$ is input heat for boiler, kJ/kg; $\nabla c_{py}$ is the smoke exhaust temperature change, K.

3.2. Calculation model of carbon sensitivity of turbine side parameters

The form of energy loss of steam turbine system is complex, which is the largest part of energy loss in the whole process of coal-fired power generation. The controllable operating parameters affecting the absolute internal efficiency of steam turbine include inlet steam parameters and turbine back pressure. The carbon sensitivity calculation model is only established for the representative superheated steam pressure $p_{gr}$, superheated steam temperature $t_{gr}$, reheated steam pressure $p_{zr}$ and reheated steam temperature $t_{zr}$.

When $p_{gr}$ changes and other parameters remain unchanged, both $p_{zr}$ and the absolute internal efficiency of the steam turbine will change. To avoid double-counting, it is considered that the change of $p_{gr}$ only changes the ideal specific enthalpy drop of the high-pressure cylinder, and the influence on the middle and low-pressure cylinders is regarded as the influence of $p_{zr}$ on the relative internal efficiency of the steam turbine. At this time, $\nabla Q_{co2}$ is:

$$\nabla Q_{co2} = Q_{co2} \cdot \phi \mu_i (p_{gr})$$  \hspace{1cm} \text{(10)}

$$\mu_i = \mu_i \cdot \mu_i$$  \hspace{1cm} \text{(11)}

$$\phi \mu_i (p_{gr}) = \sqrt{\frac{(h'_1 - h'_2) - (h_1 - h_2)}{h'_1 - h'_2}}$$  \hspace{1cm} \text{(12)}

Where, $\phi \mu_i (p_{gr})$ is the relative change of the turbine absolute internal efficiency caused by $p_{gr}$ change; $\mu_i$ is ideal thermal efficiency $= \frac{h_1 - h_2}{h'_1 - h'_2}$ and $(h'_1 - h'_2)$ are the ideal specific enthalpy drop (kJ/kg) of the high-pressure cylinder before and after $p_{gr}$ change.

3.2.1. Calculation model of carbon sensitivity of superheated steam temperature

When $t_{gr}$ is changed and other parameters remain unchanged, the changes of $t_{gr}$ only change the ideal specific enthalpy drop of HP cylinder. The calculation method of $\nabla Q_{co2}$ is the same as that of $p_{gr}$ change. It only needs to replace $\phi \mu_i (p_{gr})$ in Eq. (10) with $\phi \mu_i (t_{gr})$, and replace the ideal specific enthalpy drop of HP cylinder before and after $p_{gr}$ change in Eq. (12) with that before and after $t_{gr}$ change.

3.2.2. Calculation model of carbon sensitivity of reheated steam parameter

When one parameter of $p_{zr}$ and $t_{zr}$ changes and other parameters remain unchanged, it is considered that only the ideal specific enthalpy drop of medium and low pressure cylinders will be affected. In calculating $\nabla Q_{co2}$, the analysis principle is similar to the change of superheated steam parameters, and the calculation can be continued in the form of Eq. (10 ~ 12). It only needs to replace $\phi \mu_i (p_{gr})$ in Eq. 10 with $\phi \mu_i (p_{zr})$ or $\phi \mu_i (t_{zr})$, and replace the ideal specific enthalpy drop of high pressure cylinder...
before and after $p_{gr}$ change in Eq. 12 with that of medium and low pressure cylinder before and after corresponding parameter change.

4. Case calculation

Taking a 330MW coal-fired unit as an example, its boiler is a natural circulation drum boiler with subcritical, one-time intermediate reheat and four-corner tangential combustion. The carbon sensitivity calculation model is applied to the study of carbon emission reduction under three stable conditions: 95% load rate, 80% load rate and 65% load rate. The sensitivity of carbon emission intensity of coal-fired power supply to the efficiency and controllable operation parameters of each subsystem of the unit is analyzed. Since the coal quality data is similar when selecting the working conditions, the influence of coal quality change on $T$ can be ignored in the comparison of working conditions. The main indexes are shown in Table 1 for the thermal economy calculation of three working conditions.

| Load factor/% | Boiler efficiency/% | Absolute internal efficiency of steam turbine/% | Plant power consumption rate/% | K | $Q_{co2}$ / g · kW$^{-1} · h^{-1}$ |
|---------------|---------------------|-----------------------------------------------|--------------------------------|----|-----------------------------------|
| 65            | 92.31               | 40.96                                         | 8.12                           | 2.78| 1045.67                           |
| 80            | 93.54               | 43.65                                         | 7.84                           | 2.92| 1002.47                           |
| 95            | 93.81               | 43.94                                         | 6.99                           | 2.94| 991.58                            |

As can be seen from Table 1, when the unit load increases, the boiler efficiency and the absolute internal efficiency of the turbine increase, while the power consumption of the plant decreases; $Q_{co2}$ is negatively correlated with the load rate; for every 1% increase in the load rate, $Q_{co2}$ reduces by 1.27g/(kW·h) on average; increases by 1%, the absolute internal efficiency of the turbine increases by 1%, or the power consumption of the plant decreases by 1MW. The carbon sensitivity data corresponding to the three changes are shown in Fig. 1.

![Figure 1](image-url)  
Figure 1 Carbon sensitivity data corresponding to changes in subsystem indicators under various working conditions

In Fig. 1, with the increase of load rate, the sensitivity of $Q_{co2}$ to changes in boiler efficiency, absolute internal efficiency of steam turbine and power consumption decreases. Under the same range of variation, the sensitivity of $Q_{co2}$ to the change of absolute internal efficiency of steam turbine is about 2 times that of boiler efficiency. When the load rate is 60%, every 1MW decrease in plant power
consumption will lead to a 5.581 g/(kW•h) decrease in $Q_{CO_2}$, which indicates that plant power consumption under low working conditions has a high carbon sensitivity.

The common variation range of controllable operation parameters in actual operation of the unit is selected: taking 90% load rate as an example, the carbon sensitivity data of controllable operation parameters is shown in Table 2. The carbon sensitivity data of controllable operation parameters of boiler side and turbine side under various working conditions are shown in Fig. 2 and Fig. 2.

| Parameter change                                      | $\nabla Q_{CO_2}$/(g·kW⁻¹·h⁻¹) |
|------------------------------------------------------|---------------------------------|
| Exhaust smoke temperature drop -10K                 | 4.630                           |
| Oxygen content of exhaust smoke decreased by -1%     | 3.834                           |
| Fly ash carbon content decreased by -1%              | 3.113                           |
| Superheated steam temperature increase by 1K         | 0.281                           |
| Superheated steam pressure increase by 0.1MPa       | 0.460                           |
| Reheated steam temperature increase by 1K            | 0.246                           |
| Reheat steam pressure increase by 0.1MPa            | 0.281                           |

Figure 2  Sensitivity of CO₂ emission to controllable parameters in boiler system under different working conditions

The larger the $\nabla Q_{CO_2}$ value corresponding to the operation parameter changes, the higher the carbon sensitivity of this parameter will be. As can be seen from Table 2, under the common variation range of controllable operation parameters in the actual operation of the unit, the carbon sensitivity of controllable operation parameters on the boiler side is higher than that on the steam turbine side. In the boiler side parameters, the $\nabla Q_{CO_2}$ caused by smoke exhaust temperature change is the largest. In the steam turbine side parameters, the carbon sensitivity of superheated steam parameters is greater than that of reheated steam parameters. It can be seen from Fig. 2 that with the increase of load rate, the carbon sensitivity of controllable operation parameters at boiler side increases; $\nabla Q_{CO_2}$ caused by the change of exhaust gas temperature is the largest, and the change of $\nabla Q_{CO_2}$ caused by the change of flue gas oxygen content is the largest under different load rates.
5. Conclusion

(1) The carbon sensitivity calculation model of controllable operating parameters of coal-fired units can intuitively show the sensitivity of carbon emission intensity of coal-fired power supply to the changes of controllable operating parameters, which can provide reference for operators to design carbon emission reduction operation scheme.

(2) The carbon sensitivity of plant power consumption decreases with the increase of load rate, and has a high carbon emission reduction potential under a low load rate.

(3) Under the common variation range of controllable operation parameters in the actual operation of the unit, the carbon sensitivity of controllable operation parameters on the boiler side is higher than that on the steam turbine side at all load rates; The carbon sensitivity of exhaust temperature, exhaust oxygen content and fly ash carbon content is higher under high load rate. The carbon sensitivity of superheated steam pressure is higher than that of other steam parameters, and decreases with the increase of load rate.

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