Study on Carbon Emission Characteristics and Management Suggestions of Thermal Power Unit

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Abstract. In order to analyze the carbon emissions characteristics of power units, a simplified calculation model and an empirical fitting calculation model for carbon emission intensity of power supply is established based on the China national standard GB/T 32151.1-2015, and the reliability of the established model is verified using the measured data of carbon content per calorific value and carbon oxidation rate, which shows that the proposed model can provide ideas for rapid obtain the unit carbon emission intensity. Then typical units with different pressure levels is taken as examples to analyze the influence of sensitivity factors on carbon emission intensity of power supply based on the variable-controlling approach using the established model, which shown that energy saving and fuel control are important means to control carbon emissions. Finally, some carbon emission management suggestions are given, which provides a reference for the thermal power enterprises.

1. Introduction

China has become the world's biggest carbon emitter. In order to actively deal with climate change, China has submitted intended nationally determined contributions (INDC) [1], which states that: (1) to achieve the peaking of carbon dioxide emissions around 2030 and making best efforts to peak early; (2) to lower carbon dioxide emissions per unit of GDP 2030 by 60% to 65% from the 2005 level; To increase the share of non-fossil fuels in primary energy consumption to around 20%. Under these actions, all major industries in the country are facing enormous challenges.

The electricity industry is a major carbon emitter [2]. According to EPA data, the total emissions of electricity industry in the United States accounted for 29.7% of the total greenhouse gas emissions in 2014. In August 2015, President Obama promulgated the Clean Electricity Plan, which stipulates that the carbon emission limit of coal-fired generating units is 592 g CO₂/ kWh and the carbon emission limit of gas-fired generating units 350 g CO₂/ kWh in 2030 [3]. The Research on China Power Emission Reduction 2018 shows that the carbon dioxide emissions per unit of thermal power generation in China is about 844 g CO₂/ kWh in 2017 [4], which is far ahead of the limits of the United States. In the future, China's stock units and incremental units will face tremendous pressures and challenges.

In order to find out the carbon emission level of power generation enterprises and ensure that enterprises can cope with the carbon market calmly, this paper establishes a simple calculation model and an empirical fitting calculation model based on in-depth analysis of the carbon emission characteristics of thermal power units, which can provide a reference for rapid calculation of carbon
emission intensity of power units. And then typical units with different pressure levels are taken as example, the influence of carbon content per calorific value, carbon oxidation rate and standard coal consumption on carbon emission intensity of power supply is analyzed by variable-controlling approach, which can give suggestions for carbon emission management of power enterprises.

2. Characteristic Analysis of Coal-fired Unit

According to the calculation formula of carbon emission from fossil fuel combustion in "Requirements of the Greenhouse Gas Emission Accounting and Reporting – Part 1: Power Generation Enterprise" [5], for coal-fired units, the carbon emission from raw coal combustion can be expressed as follows:

\[ E_c = AD_c + EF_c \]  
(1)
\[ AD_c = FC_c \times NCV_c \]  
(2)
\[ EF_c = CC_c \times OF_c \times \frac{44}{12} \]  
(3)

Among that, \( E_c \) is carbon emission produced by raw coal combustion, t; \( AD_c \) is activity level of raw coal, GJ; \( EF_c \) is emission factor of raw coal, t/ GJ; \( FC_c \) is consumption of raw coal, t; \( NCV_c \) is low calorific value of raw coal, GJ/ t; \( CC_c \) is carbon content per calorific value of raw coal, tC/GJ; \( OF_c \) is oxidation rate of raw coal, %.

Carbon emission of coal combustion for condensing unit all comes from power supply. The carbon emission intensity of power supply for coal-fired unit can be expressed as follows:

\[ e_p = \frac{E_c}{P_e} \]  
(4)

Among that, \( e_p \) is carbon emission intensity of power supply, t/ MWh; \( P_e \) is power supply of coal-fired units, MWh.

Then Eq. (1) ~ (3) is introduced into Eq. (4), and both the numerator and denominator of formula is multiplied by the calorific value of the standard coal 29.307 GJ/ t at the same time, which can be expressed as follows:

\[ e_p = \frac{\{FC_c \times NCV_c / (P_e \times 29.307)\} \times CC_c \times OF_c \times \frac{44}{12} \times 29.307}{P_e} = b_c \times \alpha_c \]  
(5)

Among that, the standard coal consumption of power supply is expressed as follows:

\[ b_c = FC_c \times NCV_c / (P_e \times 29.307) \]  
(6)

The carbon emission coefficient of standard coal is expressed as follows:

\[ \alpha_c = CC_c \times OF_c \times \frac{44}{12} \times 29.307 \]  
(7)

The significance of \( \alpha_c \) is that the amount of carbon emission produced by combustion of 1 kg standard coal which is converted by the raw coal, and it is affected by the carbon content per calorific value and carbon oxidation rate of coal.

Compared with the condensing unit, the cogeneration unit is limited by the heat network dispatch, and different operating conditions have a greater impact on the unit economy and carbon emission level in different seasons. In order to analyze the carbon emission characteristics of cogeneration units, the carbon emissions are divided into the carbon emission produced by power supply and heat supply, as shown in Eq. (8).

\[ E_c = E_p + E_h \]  
(8)

Among that, \( E_p \) is carbon emission of power supply, t; \( E_h \) is carbon emission of heat supply, t.

The carbon emission intensity of heat supply is as follows:

\[ e_h = \frac{E_h}{Q_h} = b_h \times \alpha_c \]  
(9)

Among that, \( b_h \) is the standard coal consumption of heat supply, kg / GJ.

Eq. (5) and (9) shows that the main factors affecting the carbon emission intensity are the standard coal consumption and the carbon emission coefficient of standard coal. Therefore, on the one hand, for
condensing units, energy-saving measures such as transformation and operation optimization can reduce the carbon emission intensity of power supply; for cogeneration units, special attention should be paid to making full use of the heating supply period to increase the heat load, so as to improve the heating ratio and reduce the carbon emission intensity. On the other hand, the characteristics of coal have a great impact on the carbon emission of power enterprises. Different coal types have different carbon content per calorific value, resulting in different carbon emission and carbon emission intensity.

3. Calculation Model of Carbon Emission Intensity of Power Supply

According to "Requirements of the Greenhouse Gas Emission Accounting and Reporting – Part 1: Power Generation Enterprise "[5], the measured carbon content per calorific value and carbon oxidation rate should be selected to calculate the carbon emission intensity of power supply using Eq. (5), however, it is difficult to obtain this data actually in thermal power enterprise. Firstly, most power enterprises do not carry out the measurement of carbon elemental content of coal as fired, so the measured carbon content per calorific value cannot be obtained; secondly, some power enterprises lack carbon content data of ash and slag, which makes it impossible to calculate the measured carbon oxidation rate. In order to overcome the above problems, two calculation models for carbon emission intensity of power supply are established as follows. In the simplified calculation model, the carbon content per calorific value and carbon oxidation rate are both default values. In the empirical fitting calculation model, empirical fitting method is used to calculate the carbon content per calorific value, and the carbon oxidation rate is calculated by the measured values.

3.1. Simplified calculation model for carbon emission intensity of power supply

According to the Provincial Guidelines for the Compilation of Greenhouse Gases (Trial Implementation) [6], the default value of carbon content per calorific value of different coal types is shown in Table 1.

| Coal type                  | Bituminous coal | Anthracite coal | Lignitous coal |
|----------------------------|-----------------|-----------------|---------------|
| Carbon content per calorific value (tC/ TJ) | 26.18           | 27.49           | 27.97         |

In the simplified calculation model, the carbon content per calorific value is calculated with the default values of bituminous coal, anthracite coal and lignitous coal which is commonly used in power enterprises in Table 1, and the default value of carbon oxidation rate is calculated with 98%. Then the carbon emission coefficient of the standard coal $\alpha_c$ is obtained by Eq. (7) as shown in Table 2.

| Carbon emission coefficient of standard coal | Value of $\alpha_c$ (tCO$_2$/ tce) |
|---------------------------------------------|-----------------------------------|
| Bituminous coal                             | 2.757                             |
| Blending of bituminous coal and anthracite coal | a*2.757+b*2.895                   |
| Blending of bituminous coal and Lignitous coal | c*2.757+d*2.946                   |
| Anthracite coal                             | 2.895                             |
| Blending of anthracite coal and Lignitous coal | e*2.895+f*2.946                   |
| Lignitous coal                              | 2.946                             |

The boilers of power enterprises have a wide range of coal adaptable, and there is more and more power enterprises operate with blending burning of coal. For units with coal blending, the emission coefficients of standard coal can be calculated from different coal blending ratios (a-f in Table 2), and the carbon emission intensity of power supply can be rapid calculated by Eq. (5) according to the standard coal consumption of power supply and the value $\alpha_c$ in Table 2.

3.2. Empirical fitting calculation model for carbon emission intensity of power supply

Actually, for the same type of coal, the carbon content of calorific value is also quite different, therefore the simplified calculation model in 3.1 has some limitations. In order to overcome the problem of elemental carbon content data missing, 57 anthracite coal, 1612 bituminous coal and 1157 lignitous coal
were used as samples to fit in this paper and obtain an empirical fitting calculation method of elemental carbon content based on industrial analysis, sulphur content and calorific data as shown in equation (10):

\[ C_d = 35.411 - 0.341A_d - 0.199V_d - 0.412S_{t,d} + 0.1632Q_{gr,d} \]  
(10)

Among that, \( A_d, V_d \) and \( S_{t,d} \) are respectively the ash, volatile and sulphur content of the dry base of burning coal, \%; \( Q_{gr,d} \) is the high caloriific value of the dry base of burning coal, kJ/g.

And carbon content per calorific value can be expressed as Eq. (11):

\[ CC_c = \frac{C_d}{NCV_c} \times \frac{(100-M_{ar})}{100} \]  
(11)

Among that, \( M_{ar} \) is the moisture content of received base, %.

Considering that most power enterprises has statistical data of carbon content and production in ash and slag, the empirical fitting calculation model of carbon oxidation rate adopts the measured data by the national standard, as shown in Eq. (12).

\[ OF_c = 1 - \left( \frac{G_s \times C_s + G_a \times C_a}{\eta} \right) \times 10^6 / (FC_c \times NCV_c \times CC_c) \]  
(12)

Among that, \( G_s \) and \( G_a \) are respectively the production of ash and slag, t; \( C_s \) and \( C_a \) are respectively the carbon content of ash and slag, \%; \( \eta \) is the efficiency of the dust collector, %.

When the Eq. (10) ~ (12) of carbon content per calorific value and carbon oxidation rate is introduced into Eq. (1) ~ (5), the empirical fitting calculation data of carbon emission intensity of power supply can be calculated in this section.

3.3. Model reliability verification

An ultra-high pressure circulation fluidized bed (CFB) condensing unit is taken as example in this section, and the coal of the unit is lignite. The power enterprise has measured carbon content data of calorific value, and has statistical data of production and carbon content of ash and slag. According to Eq. (12), the measured carbon oxidation rate can be calculated, and the carbon emission intensity of power supply can be calculated respectively using simplified calculation model and empirical fitting calculation model by Eq. (5), which is shown in Fig. 1 and Fig. 2.

**Figure 1.** Comparing of carbon content data of calorific value calculated by established model.

**Figure 2.** Comparing of carbon oxidation rate calculated by the established model.
As shown in Fig. 1 and 2, the carbon content per calorific value and carbon oxidation rate of the simplified model are default values, which are somewhat different from the theoretical values. While the trend of empirical fitting data are consistent with the measured values and are close to each other. And it is also noted that the actual carbon oxidation rate is far less than the default value 98% because the unit is an ultra-high pressure unit. The comparison of power supply carbon emission intensity is shown in Fig. 3.

![Figure 3. Reliability of the calculation model.](image)

As shown in Figure 3, compared with theoretical value, the maximum error of power supply carbon emission intensity obtained by simplified calculation model is nearly 10%. While the empirical fitting model has the error of less than 5% in calculating the carbon emission intensity of power supply and the changing trend is consistent with the measured data. The reason is that the simplified calculation model does not consider the changing of coal carbon content and the carbon oxidation degree, and for an ultra-high pressure unit, the carbon oxidation rate is far less than 98%, which results in high carbon emission intensity of power supply. Therefore, when the measured data of elemental carbon in power enterprises cannot obtain, the empirical fitting calculation model can better reflect the carbon emission level of the unit.

4. Sensitivity Analysis of Power Supply Carbon Emission Intensity

In this paper, typical units are selected as an example to calculate and analyze the impact of key factors on carbon emission intensity of power supply using empirical fitting calculation model based on the variable-controlling approach.

4.1. Effect of carbon content per calorific value on carbon emission intensity of power supply

The carbon content per calorific value and the carbon emission intensity of power supply is calculated under different pressure and capacity levels of the unit, and the effect of carbon content per calorific value on carbon emission intensity of power supply is analyzed under the condition of constant coal consumption and carbon oxidation rate based on the variable-controlling approach as shown in Fig. 1.

![Figure 4. Effect of carbon content per calorific value on carbon emission intensity.](image)
It can be seen from the Fig. 4 that: (1) the carbon emission intensity of power supply for higher-parameter and larger-capacity units is obviously at a low level; (2) the lower carbon content per calorific value is, the lower carbon emission intensity of power supply becomes, and impact of carbon content per calorific value increases gradually with the reduction of energy consumption level of units.

4.2. Effect of carbon oxidation rate on carbon emission intensity of power supply

It can be seen from Fig. 5 that: (1) for the higher-parameter and larger-capacity units, the measured carbon oxidation rate is higher than that for the with lower-parameter and lower-capacity units; (2) the carbon oxidation rate rises by 1%, and the carbon emission intensity and total carbon emission of the unit also increase by 1%.

![Figure 5. Relationship between carbon oxidation rate and carbon emission intensity.](image)

4.3. Effect of standard coal consumption on carbon emission intensity of power supply

Compared with bituminous coal-fired units (lower carbon content per calorific value), lignitous coal-fired units (higher carbon content per calorific value) are more sensitive to the change of standard coal consumption, and it is means that per unit change in coal consumption has more effects on carbon emission intensity of power supply for lignitous coal-fired units than bituminous coal-fired units.

![Figure 6. Relationship between standard coal consumption and carbon emission intensity.](image)

5. Conclusion

Energy saving and fuel control are the main means for power enterprises to control carbon emissions. It is suggested that all power enterprises should estimate the carbon emission level of enterprises accurately, and enhance carbon emission management level as soon as possible.
5.1. Enhancing the construction of organizational system
The start-up of the national carbon market has put forward specific requirements on carbon emission monitoring, reporting, verification (MRV), and quota allocation. It is suggested that power enterprises should be equipped with dedicated personnel to manage carbon emission, and enhance the reserve of talents to provide that enterprises has the ability to cope with the carbon market.

5.2. Enhancing the management of coal consumption of power supply
Coal consumption of power supply is the key factor affecting the carbon emission intensity. It is suggested that power enterprises should enhance the management of coal consumption of power supply, and implement the energy saving and consumption reduction to reduce the carbon emission intensity.

5.3. Carrying out the detection of elemental carbon content
The measured carbon content of calorific value is the unified requirement of future quota allocation and fulfillment in carbon market. It is suggested that power enterprises should establish an element carbon content detection and supervision system, and carry out the detection of element carbon content in accordance with the requirements of national standards, which can improve the accuracy of carbon emission calculation.

5.4. Enhancing the control and optimization of fuel
High-quality and low-carbon fuels have a positive impact on unit safety, economy and low-carbon operation. Power enterprises can gradually increase the proportion of high-quality and low-carbon fuels according to the actual situation, so as to control the carbon dioxide emissions from the source.

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