A Control Strategy of the Air Flow Rate of Coal-Fired Utility Boilers Based on the Load Demand

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1. INTRODUCTION

In 2017, the proportion of coal in total electricity generation was 60% in China. This proportion will be reduced to 40% by 2040 to mitigate the energy crisis and reduce pollutant emissions.1 China’s growing energy needs are increasingly met by renewables while the coal demand is decreasing, which implies that coal-fired power plants need to improve their ability to utilize fossil fuels in a flexible and efficient manner. High-quality combustion control systems for coal-fired utility boilers keep the primary process variables at optimal levels so that the boiler operates with high efficiency and produces low emissions. The requirements of boiler control include rapid adjustment of the air distribution on the combustion process using numerical simulations and experiments.10–13 Li et al.14 developed a computational fluid dynamics model to study the effects of the primary air ratio (PAR) on boiler performance. The results showed that the combustion process deteriorated with an increase in the PAR. However, in the primary burner region and the region above the fire, the combustion characteristics exhibited a parabolic trend as the PAR increased. The primary

At present, some power plants still use manual control mode in air flow rate control. Although the operating personnel can adjust the air flow rate into the furnace online according to the oxygen content of the flue gas, which can basically ensure the air supply required for combustion, the automatic control of the air flow rate undoubtedly has advantages in all aspects. Computational modeling of pulverized coal-fired boilers provides references for improving and optimizing the air flow rate.4–9 Many scholars also have conducted studies on the effect of the air distribution on the combustion process using numerical simulations and experiments.10–13 Li et al.14 developed a computational fluid dynamics model to study the effects of the primary air ratio (PAR) on boiler performance. The results showed that the combustion process deteriorated with an increase in the PAR. However, in the primary burner region and the region above the fire, the combustion characteristics exhibited a parabolic trend as the PAR increased. The primary
reason for the deterioration of the combustion behavior was the ratio of the primary and secondary air energy input rather than the total air energy input. These studies of the air distribution influence (especially for the influence of primary and secondary air) on the combustion control solved some practical problems, but it is difficult to strike a balance between air distribution from combustibles consume at different operating loads.

More research on boiler air supply are still based on the understanding that optimizing the air flow rate has a great correlation with changes in fuel quality, and the air flow rate needs to be adjusted according to changes in coal quality. For instance, Blondeau et al. 16 proposed that the air/fuel equivalence ratios in large pulverized coal-fuel boilers are crucial to optimize the combustion process while keeping the primary pollutant emissions at an acceptable value. The ideal air/fuel ratio is obtained by calculating the air demand based on the coal flow, and modifications are made based on the oxygen concentration in the flue gas. However, the air/fuel ratio depends on the type of coal and the type of boiler. It is especially difficult to adjust the air flow rate for a fixed air/fuel ratio when the unit load changes rapidly. In addition, changes in the oxygen concentration in the flue gas are not only caused by the heat output of the fuel but also by starting, stopping, and tripping the pulverizing system, as well as soot and decoking.

In previous studies, the air demand was calculated based primarily on a single variable, which is not easy to control; therefore, this is not the most desirable method. A key aspect of the control of coal-fired power generation units is load control; the energy conversion stage, from the release of chemical energy during fuel combustion to electrical energy used to power the turbo generator, should be adjusted according to the load demand. Reference 17 gives an approximate view that the annular air fuel should be controlled by the boiler load. For combustion in a coal-fired boiler, the total air flow rate should be adjusted based on the fuel amount. Therefore, studies should focus on the control strategy of the air demand in a coal-fired boiler. In this study, a new concept of the theoretical air flow rate based on the calorific value of coal is proposed, theoretical calculations are performed, and experiments are conducted. The results of this study provide a strategy for controlling the air flow rate during combustion in coal-fired utility boilers based on the load demand.

2. RESULTS AND DISCUSSION

2.1. Principles for Air Flow Rate Control Strategy. The combustion process in a furnace involves fuel and oxygen. The other components of the air do not participate in the combustion process and are considered part of the stack loss, which is discharged along with the combustion product through the chimney. In regular combustion and steam generator applications, the oxygen comes from the air in the atmosphere. Since the combustion is a simple oxidation process, the amount of oxygen is considered in the subsequent analysis. The corresponding amount of air required for the combustion is easily calculated.

There are two methods of combustion calculations: the first is known as the molar method, which is based on the chemical relationships, and the second method uses the firing of MJ/kg as a basis for the calculation. It is customary for industrial boilers to use units of mass rather than moles for expressing the air demand quantity. If the combustion calculations are conducted using the molar method, the results are usually converted to 1 kg/100 kg fuel.

Items expressed in fuel-based units can be normalized using fuel-based inputs. The concept of mass per unit input is valuable in determining the impact of different fuels on combustion performance, which is especially useful for theoretical air calculations.

The theoretical air requirement for various fuels on a mass per mass of fuel basis is listed in the first column of Table 1. The concept of mass per unit input is valuable in determining the impact of different fuels on combustion calculations. As shown in Table 1, in the third column, the results show that there are significant differences in the theoretical air for different fuels. However, when the theoretical air is converted to the mass per unit heat input, in the fourth column, there is little difference in the theoretical air volume for different fuel types.

| Fuel Type       | HHV  (MJ/kg) | theoretical air from mass per fuel basis (kg/kg) | theoretical air from mass per unit heat input (kg/MJ) |
|-----------------|--------------|--------------------------------------------------|------------------------------------------------------|
| bituminous coal | 0.0279       | 9.07                                             | 0.3250                                               |
| subbituminous coal | 0.0186     | 6.05                                             | 0.3250                                               |
| oil             | 0.0428       | 13.69                                            | 0.3207                                               |
| natural Gas     | 0.0507       | 15.74                                            | 0.3104                                               |
| wood            | 0.0136       | 3.94                                             | 0.2902                                               |
| MSW and RDF     | 0.0128       | 4.13                                             | 0.3225                                               |
| carbon          | 0.0328       | 11.51                                            | 0.3508                                               |
| hydrogen        | 0.1419       | 34.29                                            | 0.2416                                               |

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is the number of moles of C in KJ/g, and \( \frac{105}{HHV} \) is the amount of coal required to generate 100 MJ of heat. As the main combustible element, carbon is the primary contributor to heat during the combustion process. If the calorific value of the other elements in the coal is calculated based on the carbon content, which means that all the heat released by coal combustion is produced by carbon, it is called the equivalent carbon content.

The higher heating value estimates (HHVE) of anthracitic, bituminous, and lignite coal are listed in Table 2.\(^{19,20}\)

We use the first approximation formula as an example; the equivalent carbon content of the meta-anthracite coal is calculated as:

\[
C_e^r = \frac{1}{78.1} [78.1C' + 320H' + 22(S' - O')] - 8(A'^r - 10)
\]

\[C_e^r \times 10^3/HHV\] is the equivalent carbon content required during the combustion to generate 100 MJ of heat. The other ranks of coal are calculated in the same manner. The air volume required during the combustion based on the equivalent carbon content is calculated as follows:

\[
Q_e = \frac{C_e^r \times 10^3 \times 22.4}{12 \times 0.21} = 8.8 \times 10^3 \times C_e^r
\]

The theoretical air volume required during combustion to generate 100 MJ of heat was determined for the 124 coal samples with 1 to 42% ash. The samples consisted of 28 anthracite, 77 bituminous, and 19 lignite coal samples. The results calculated based on the HHV and the equivalent carbon content are shown in Figures 1–3. It is evident that the trends of the curves of most coal samples are similar.

The mean theoretical air volumes of the anthracite samples calculated based on the two methods are 26,486 and 26,876 L, respectively (Figure 1a). The respective values for the 77 samples of bituminous coal are 25,668 and 26,480 L (Figure 2a), and the respective values of the 19 samples of lignite coal are 25,439 and 26,658 L (Figure 3a). Although the theoretical air volumes of the three types of coal calculated based on the HHV are slightly higher than those of the other method, the two results have the same trend, and the deviations are small.

As shown in Figure 1b, the relative deviations from the theoretical air volume of the anthracite samples calculated based on the two methods are ±2.91 and ±1.76% at the 95% confidence interval. The respective values for the bituminous samples are ±2.97 and ±1.81%, and the respective values for the

**Table 2. Classification of Coal Types Based on the Higher Heating Value Estimates**

| class          | group            | rank                  | approximation formulas                                      |
|----------------|------------------|-----------------------|-------------------------------------------------------------|
| anthracite     | meta-anthracite  | \( A'^r > 10\% \), \( C'^r \geq 95\% \) | \( HHVE = \frac{105}{HHV} [78.1C'^r + 320H'^r + 22(S'^r - O'^r)] - 8(A'^r - 10) \) |
| anthracite     | anthracite A     | \( A'^r \leq 10\% \), \( C'^r \geq 95\% \) | \( HHVE = \frac{105}{HHV} [78.1C'^r + 320H'^r + 22(S'^r - O'^r)] - 8(A'^r - 10) \) |
| anthracite     | anthracite B     | \( A'^r > 10\% \), \( C'^r < 95\% \) | \( HHVE = \frac{105}{HHV} [80C'^r + 320H'^r + 22(S'^r - O'^r)] - 8(A'^r - 10) \) |
| anthracite     | anthracite C     | \( A'^r \leq 10\% \), \( C'^r < 95\% \) | \( HHVE = \frac{105}{HHV} [80C'^r + 320H'^r + 22(S'^r - O'^r)] - 8(A'^r - 10) \) |
| bituminous     | bituminous A coal| \( A'^r > 10\% \), 20\% < \( V'^r < 50\% \) | \( HHVE = \frac{105}{HHV} [80C'^r + 310H'^r + 22S'^r - 260O'^r - 4(A'^r - 10) \) |
| bituminous     | bituminous B coal| \( A'^r > 10\% \), 14\% < \( V'^r < 20\% \) | \( HHVE = \frac{105}{HHV} [80C'^r + 310H'^r + 22S'^r - 250O'^r - 7(A'^r - 10) \) |
| bituminous     | bituminous C coal| \( A'^r \leq 10\% \), 20\% < \( V'^r < 50\% \) | \( HHVE = \frac{105}{HHV} [80C'^r + 310H'^r + 22S'^r - 260O'^r - 6(A'^r - 10) \) |
| lignite        | lignite A coal   | \( A'^r > 10\% \), \( V'^r > 40\% \) | HHVE = \( 80C'^r + 305H'^r + 22S'^r - 250O'^r - 7(A'^r - 10) \) |
| lignite        | lignite B coal   | \( A'^r \leq 10\% \), \( V'^r > 40\% \) | HHVE = \( 80C'^r + 305H'^r + 22S'^r - 260O'^r - 6(A'^r - 10) \) |

\(C', H', S', O', V'\), and \(A'^r\) are the contents of carbon, hydrogen, sulfur, oxygen, volatile matter, and ash, respectively, in weight percent.

**Figure 1.** (a) Theoretical air volume and (b) relative deviation from the theoretical air volume required for generating 100 MJ of heat for the 28 anthracite coal samples.
Theoretical air volume and relative deviation from the theoretical air volume required for generating 100 MJ of heat for the 77 bituminous coal samples. (a) Theoretical air volume (L) and (b) relative deviation from the theoretical air volume (%).

Figure 2. (a) Theoretical air volume and (b) relative deviation from the theoretical air volume required for generating 100 MJ of heat for the 77 bituminous coal samples.
mass fraction of oxygen in the air is 23.2%, and the air/carbon ratio (mass ratio) is approximately \((32/0.232)/12 = 11.5\) kg/kg. This means that 11.5 kg of air is used to burn 1 kg of carbon. This ratio is roughly constant for different types of coal, unlike the air/coal ratio, which is significantly different for different coal types. The carbon in the air/carbon ratio is defined as the carbon that burns completely burn to generate heat and excludes the carbon that is not completely burned.

In summary, the air flow rate required for different types of coal during combustion to produce the same amount of heat is the same and is a function of the unit load. The proposed air/carbon ratio is a better indicator than the air/coal ratio to assess combustion in a furnace. Note that the air/carbon ratio is not a constant quantity. Thus, the behavior of the air and coal in a coal-fired boiler is decoupled.

The second concept that is proposed is the air-heat equivalent, which is the ratio of the net calorific value of 1 kg of coal to the theoretical air flow rate required for its complete combustion. The air-heat equivalence represents the heat released by coal burning steadily and continuously with 1 kg of air in a furnace.

The theoretical air mass was calculated using the low calorific value of the fuel as follows:

\[
m_a = 0.115(C_{ar} + 0.375S_{ar}) + 0.342H_{ar} - 0.0431O_{ar} \tag{4}\]

where \(C_{ar}, S_{ar}, H_{ar}\) and \(O_{ar}\) are on an as-received basis. Subsequently, the air-heat equivalent of different types of coal samples can be calculated. Figure 4a shows the air-heat equivalent of 205 Chinese coal samples (on an as-received basis); the mean air-heat equivalent is 2.93 MJ/kg.

The air-heat equivalent is combined with the air/carbon ratio to determine the heat of the carbon reaction, which is the heat released by the complete combustion of 1 kg of carbon. The functional relationship between the parameters is expressed as:

\[
\frac{m_{air}}{m_{carbon}} = \frac{Q_{net,ar}}{m_{air}} = 11.5 \times 2.93 = 33.93, \text{ MJ/kg} \tag{5}\]

where \(m_{air}/m_{carbon}\) is the air/carbon ratio, \(Q_{net,ar}/m_{air}\) is the air-heat equivalent, and \(Q_{net,ar}/m_{carbon}\) is the heat of the carbon reaction, which is approximately equal to a constant value of 33.93 MJ/kg. The results of the equation show that the heat of reaction during the complete combustion of carbon to carbon dioxide is 393.6 MJ/kmol. The heat of the carbon reaction per unit mass is 393.6(MJ/kmol)/12(kg) = 32.8MJ/kg, indicating that the difference in the heat of the carbon reaction for the two calculation methods is only 1.13 MJ/kg.

The air-heat equivalent of 205 Chinese coal samples is shown in Figure 4a, and the relative deviation from the air-heat equivalent is presented in Figure 4b, which shows that there are 180 coal samples with positive and negative deviations of less than 5%, accounting for more than 87.8% of the total coal samples. The maximum positive and negative deviations are 7.74 and –7.66%, respectively. The reason for the deviation larger than 5% is that the amount of volatile matter of the coal is either very high or very low, i.e., >36% or <10%. If the amount of volatile matter of the coal samples is in the range of 10—36%, the relative deviation from the air-heat equivalent that is less than 5% accounts for more than 98.1% of the total coal samples.

It has been shown that the air-heat equivalent is roughly constant for different types of coal in China, and the mean value is 2.93 MJ/kg for the 205 coal samples. The interpretation of the air-heat equivalent is that the heat released by any type of coal burning steadily and continuously with 1 kg of air in a confined space (furnace) is approximately equal to a constant value of 2.93 MJ/kg. For different types of coal, the errors of the air-heat equivalent are within ±5%.

The required air flow rate can be calculated based on the relationship between oxygen, the heat release, and the air volume. In the air-heat equivalent method, the control strategy for the air flow rate during combustion is based on a per-unit basis rather than on changes in the air flow rate based on different coal qualities.

2.2. Effectiveness of the New Air Flow Rate Control Strategy. We use the proposed control strategies of the air flow rate and conduct an experiment in a 300 MWe coal-fired power generation plant. The plant includes a tangentially-fired pulverized coal boiler with a rated load of 300 MW. In practical boiler operations, the boiler consumes 136.1 t/h of coal under
boiler maximum continuous rating (BMCR) condition to produce 1025 tons of steam with a pressure of 17.4 MPa.

The original operating parameters of the power plant as the load increases from 160 to 240 MW over 2 h are shown in Figure 5. A forced draft fan motor current (FFC) was used during boiler
The results show that the FFC and coal flow change with the power output. However, the coal flow exhibits larger fluctuations than the FFC, indicating that the air/coal ratio is out of balance at certain times. This imbalance results in large fluctuations of the main steam pressure, which, in turn, exacerbates the combustion overshoot in the furnace.

At a given load, the objective of the fuel amount adjustment is to ensure that the total heating value of the coal supplied remains stable. The objective of the air volume control is to ensure that the air supply is optimal for combustion. As described above, the air flow rate is a function of the unit load. This functional relationship was analyzed and summarized using a large sample size of historical operating data of the unit.

The relationship between the power output/fuel ratio \( (P/F) \) and the air/fuel ratio \( (A/F) \) changed over time for typical loads, as shown in Figure 6. The raw historical operating data cover 2 weeks with a sampling time of 6 s. Filtering of the raw data was performed to minimize the noise effects. It is observed that the \( A/F \) has the same trend as the \( P/F \) at the same load, showing a good linear relationship. This result indicates that the combustion adjustment in the furnace is satisfactory during combustion to regulate the air flow rate entering the furnace. The results show that the FFC and coal flow change with the power output.

**Figure 6.** Relationship between the power output/fuel ratio \( (P/F) \) and the air/fuel ratio \( (A/F) \) for typical loads: (a) 270, (b) 280, (c) 290, and (d) 300 MW.

**Figure 7.** Relationship between the forced draft fan motor current (FFC) and the load.

```python
import matplotlib.pyplot as plt
import numpy as np

# Sample data for FFC and load
load = np.array([140, 160, 180, 200, 220, 240, 260, 280, 300, 320])
FFC = np.array([24, 25, 26, 27, 28, 29, 30, 31, 32, 33])

# Plotting the data
plt.plot(load, FFC, 'o', label='FFC')
plt.plot(load, np.poly1d(np.polyfit(load, FFC, 1))(load), label='Polynomial fit of FFC')
plt.xlabel('Load (MW)')
plt.ylabel('FFC (A)')
plt.legend()
plt.show()
```
this period, which is also the basis for the calculation of the amount of air flow rate supply for different loads.

The larger value of the P/F shows that the air flow rate matching is appropriate at this time, and the power generation efficiency per unit of fuel is high. At a given load, the air flow rate can be calculated using 80% of the maximum value of the P/F. The reason for choosing 80% of the maximum value of the P/F is that the generating power of the unit is relatively high, and this proportion leaves an error margin for data analysis. The air flow rates of the FFC at loads of 270, 280, 290, and 300 MW are 29.46, 30.55, 31.89, and 32.98 A, respectively.

The FFC value for different loads is calculated using the same method; the results are shown in Figure 7. The unit load ranges from 150 to 300 MW with 10 MW intervals, adding up to 16 data points.

The functional relationship between the FFC and the unit load is expressed as:

\[
FFC = 3.2478 \times 10^{-6} \times \text{Load}^3 - 1.97 \times 10^{-3} \times \text{Load}^2 + 0.4354 \times \text{Load} - 7.7885
\]  

(6)

The amount of air flow rate supply for different loads can be calculated by eq 6. The acronym FFC_{ori} denotes the target value of the FFC. The proposed control strategy of the air flow rate based on the load demand is shown in Figure 8; it is referred to as the coordinated control system (CCS).

In Figure 8, FFC_{ori} is the original value of the FFC of the original strategy. FFC_{tar} is the target value of the amount of air flow rate supply for different loads calculated by eq 6. FFC deviation as PID control output can be calculated based on the difference between the original and the target FFC, and the values of proportional term. FFC_{tar} values that are higher or lower than FFC_{ori} indicate that either less or more air flow rate was supplied to the furnace, representing an undesirable combustion regulation process that can be improved. Then, the FFC deviation was multiplied by the modification coefficient range from zone to 1 depending upon actual operating conditions. Finally, the FFC_{opt}, which is the optimized value of the FFC, was obtained after compensating for the FFC_{ori}. Figure 9 shows the transient processes of the main parameters of the power plant after FFC_{opt} was used in the CCS in the field test. The test was conducted using the same load adjustment as in Figure 5 to determine the effects of combustion optimization; the modification coefficient was 0.9.

As shown in Figure 9, FFC_{opt} has almost the same trend as the power output. The reason is that the FFC_{ori} values that are higher or lower than FFC_{tar} are modified by the optimization control circuit, as shown in Figure 8. The main steam pressure changes consistently with the power output with no time delay, and the fluctuation of the pressure is approximately 0.08, 0.20, 0.12, and 0.17 MPa when the power output remains at 160, 180, 220, and 240 MW, respectively.

A comparison with Figure 5 shows that the overshoot magnitude of the coal flow is significantly less than that for the original strategy. In the original control strategy, the adjustment of the coal flow occurs earlier than the adjustment of the air flow rate when the load increased, resulting in a lag in the power output and main steam pressure. This result indicates that the rapidly increasing fuel has not been converted into energy. The performance is improved after the introduction of the air flow
3. CONCLUSIONS

In this study, we investigated the relationship between the calorific value of coal and the theoretical air flow to develop a control strategy of the air demand in a coal-fired boiler. An experiment was conducted to investigate the performance of the proposed method in a 300 MWe power generation plant. The main conclusions are as follows:

- The theoretical air volume required for generating the same amount of heat during combustion is the same for different types of coal. The air flow rate is adjusted on a per unit basis, and the quality of the coal does not have a significant impact on the total air flow rate. Therefore, the air supply of the boiler operating at a given load is nearly unchanged.

- We improved on the concept of the air/coal ratio and proposed the concept of the air/carbon ratio, which refers to the ratio of the mass of air to the mass of carbon during complete combustion; the ratio is approximately 11.5 kg/kg (mass ratio). We also proposed the use of the air-heat equivalent, which is the heat released by any type of coal burning steadily and continuously with 1 kg of air in a confined space (furnace); the mean air-heat equivalent is approximately 2.93 MJ/kg.

The results of the experiments conducted in a 300 MWe coal-fired power generation plant showed that the use of the control strategy of the air flow rate in the CCS improved the stability of the main steam pressure and mitigated the fluctuations of the coal flow. The results of this study provide a reference for the future development and improvement of strategies to control the air flow rate for coal-fired utility boilers.

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Notes
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