Fuel characteristics and explosiveness analysis of pulverized coal industrial boilers in China

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Abstract. Pulverized coal industrial boilers are widely used in China in recent years for high thermal efficiency and suitable for contract energy management, especially in service amount is growing fast in regions like Shanxi, Gansu, Shandong, Tianjin, Liaoning, Hebei, etc. Considering the existing operational safety issues of pulverized coal fired industrial boiler, this article researched the relationship between fuel characteristics including caloric value, volatile, ash, moisture and powder explosion in order to explore and analysis in service pulverized coal industrial boilers explosiveness.

1. Introduction

Currently, developed countries take oil-fired or gas-fired industrial boilers as primary, coal-fired industrial boilers are still applied with high standard technology and management in developed countries and regions such as America and Europe. Germany shares a similar type of energy composition with China, in which the chain-grate boiler has a significant proportion[1]. America has 3195 coal-fired industrial boilers. The chain-grate boilers mainly consume block coals selected by washing. The new industrial diagnosis and automatic control technology leads chain-grate boilers’ automatically adjusts the running and reaches the boiler efficiency up to 78%[2]. The adoption of low-sulfur and low-ash coal, the high-efficiency dust removal, desulphurization equipment, the natural gas re-burning and SCR equipment can reduce the emission of NOx and reach the standard of coal pollutants emission[3].

Small and Medium pulverized coal industrial boiler technology be mature in the late 1990s and widely applied in Germany and France. After twenty years of developing, Germany has wholly commercialized pulverized coal industrial boilers and developed many technique standards[4].

China only has a ten-year history of pulverized coal industrial boiler from public documents. Relevant code and standards are incomplete. Current safety standard TSG G0001-2012 Boiler Safety Technology Supervisory Regulations cites GB/T5203 Technical Code for Explosion Proof Design of Coal and Pulverizing System in Thermal Power Plant, covers little about pulverized coal industrial boiler and mainly about the pulverized coal power plant boiler, especially about the powder-making system. Explosion-proof standard of pulverized coal industrial boiler follows T/CEEIA 221-2013 Pulverized Coal Industrial Boiler and Its System. The standard provides the burner ignition sequence, and furnace safeguard supervisory system (blowing before the fire, fire alarm, and blowing after the fire) standards above are formed before 2013 and mainly about power plant boilers. Standards and regulations about pulverized coal industrial boiler are little[5, 6].
2. The explosiveness of coal power

The explosiveness of coal power means the difficulty of detonation and the intention of explosion pressure. To the boilers that consume inflammable coal, their explosiveness depends on the properties of coal powder. Explosive accident of pulverized coal industrial boiler usually happens at the start, rundown, and discontinue of powder. The explosiveness of coal power depends on the flammability, ash content, humidity, fineness, temperature, concentration, and the oxygen level of the primary mixture. The characteristic ignition index generally values the explosiveness of the coal powder [1].

2.1 Explosiveness of coal powder and Explosive index

Relevance between explosiveness of coal powder and Explosive index is formulated in DL/T5145-2012 Technical Regulation for Design and Calculation of Pulverizing System in Thermal Power Plant.

Explosive index is calculated according to equation as below.

\[ K_d = \frac{V_d}{V_{vol,que}} \]  
\[ V_{vol,que} = \frac{V_{vol} \left(1 + \frac{100 - V_{daf}}{V_d}\right)}{100 + V_{vol} \frac{100 - V_{daf}}{V_d}} \]  
\[ V_{vol} = 1260 \times 4.187 / Q_{vol} \]  
\[ Q_{vol} = \left(\frac{Q_{net,v,daf} - 7850 \times 4.187 FC_{daf}}{V_{daf}} \right) / V_{daf} \]

- \( K_d \) —— Explosive index;
- \( V_d \) —— Dry basis volatile matter of coal, %;
- \( V_{vol,que} \) —— Lower limit of combustible volatiles required for combustion (Ash and fixed carbon are considered), %;
- \( V_{vol} \) —— Lower limit of combustible volatiles required for combustion (Ash and fixed carbon are not considered), %;
- \( Q_{vol} \) —— Calorific value of volatile matter, kJ/kg;
- \( Q_{net,v,daf} \) —— Low calorific value of coal on dry ash-free basis, kJ/kg;
- \( FC_{daf} \) —— Fixed carbon content of coal on dry ash-free basis, %;
- \( V_{daf} \) —— Dry ash-free volatile content of coal, %.

| Explosive index | extreme low explosivity |
|-----------------|-------------------------|
| \( K_d \) ≤ 1.0 | extreme low explosivity |
| 1.0 < \( K_d \) ≤ 3.0 | very low explosivity |
| 3.0 < \( K_d \) ≤ 7.0 | low explosivity |
| 7.0 < \( K_d \) ≤ 12.0 | medium explosivity |
| 12.0 < \( K_d \) < 17.0 | high explosivity |
| \( K_d \) ≥ 17.0 | very high explosivity |

2.2 Explosive index and Ignition Temperature of Pulverized Coal Gas Flow

Ignition Temperature of Pulverized Coal Gas Flow (IT) combines the influence of flammability and ash content, can broadly represent Explosive index under certain humidity, fineness, temperature, and concentration. Volatile matter and explosibility shares relativity, so volatile content of coal is an
approximate judgment of Explosive index. The table 2 lists DL/T5145-2012 Technical Regulation for Design and Calculation of Pulverizing System in Thermal Power Plant, gives reference value between coal explosiveness and Explosive index.

Table 2. The relationship between the explosiveness of pulverized coal and the ignition temperature of pulverized coal air flow and dry ash-free volatile matter

| Explosive index of pulverized coal | Ignition temperature of pulverized coal gas IT (°C) | Dry ash-free volatile content Vdaf (%) |
|-----------------------------------|-----------------------------------------------|-------------------------------------|
| Kdaf ≤ 1.0                        | IT ≥ 800                                       | Vdaf ≤ 6.0                          |
| 1.0 < Kdaf ≤ 3.0                  | 800 > IT ≥ 780                                 | 6.0 < Vdaf ≤ 10.0                   |
| 3.0 < Kdaf ≤ 7.0                  | 780 > IT ≥ 750                                 | 10.0 < Vdaf ≤ 15.0                  |
| 7.0 < Kdaf ≤ 12.0                 | 750 > IT > 720                                 | 15.0 < Vdaf ≤ 20.0                  |
| 12.0 < Kdaf < 17.0                | 720 > IT > 680                                 | 20.0 < Vdaf < 25.0                  |
| Kdaf ≥ 17.0                       | IT ≤ 680                                       | Vdaf ≥ 25.0                         |

2.3 Explosive index

Russian all-Russian Thermal Engineering Research Institute has a Long term experimental study about explosion characteristics of pulverized coal, proposed an engineering evaluation method for explosiveness of pulverized coal for power fuel different that China’s explosive index, and formed a standard.

This explosiveness calculated according to equation as below.

\[ K_f = \frac{V_d}{\mu_{d,V,A}} \]  \hspace{1cm} (6)

\[ \mu_{d,V,A} = \left(1 + \frac{100 - V_d}{V_d}\right) \frac{100}{100 + \mu_L \frac{100 - V_d}{V_d}} \]  \hspace{1cm} (7)

\[ \mu_L = \frac{1260}{Q_f} \]  \hspace{1cm} (8)

\[ Q_f = \frac{Q_{net,daf} - 329(C_{daf} + H_{daf} + O_{daf} - V_{daf})}{V_{daf}} \]  \hspace{1cm} (9)

- \( V_d \) —— Volatile content of coal on dry basis, %;
- \( \mu_{d,V,A} \) —— the lower limit concentration of the flame spread in the combustion state when the volatiles containing ash and coke are mixed with air, % (In addition to volatile components, there are ash and coke in the pulverized coal. They hardly participate in the reaction in the process of rapid explosion, but the ash consumes part of the heat, so it will increase the lower limit of flame expansion);
- \( \mu_L \) —— the lower limit concentration of the flame spread in the combustion state when the volatiles without ash and coke are mixed with air, %;
- \( Q_f \) —— Calorific value of volatile matter, kJ/kg;
- \( Q_{net,daf} \) —— Calorific value of dry ash-free base coal, kJ/kg;
- \( C_{daf} \) —— Carbon content of dry ash free base coal, %;
- \( H_{daf} \) —— Hydrogen content of dry ash free base coal, %;
- \( O_{daf} \) —— Oxygen content of dry ash free base coal, %;
- \( V_{daf} \) —— Volatile content of coal on dry ash-free basis, %.
3. Pulverized coal analysis data

36 boilers in Shanxi, Hebei, Shandong, Sichuan, Shanghai, Gansu, Liaoning, Jiangsu and other provinces were tested for coal quality, the test data are as below.

3.1 Analysis of calorific value

As can be seen from Fig.1, above the red line is the third-class bituminous coal, and below the red line is the second-class bituminous coal. In China, the coal used in pulverized coal industrial boilers is mainly AIII bituminous coal, which accounts for more than 90%, AII bituminous coal accounts for 5% and anthracite accounts for 5%. The main range of calorific value is 22000kJ/kg-28000kJ/kg.

![Calorific value of pulverized coal](image1.png)

Fig.1 Distribution of calorific value of pulverized coal used in boilers in different areas

3.2 Ash analysis of coal

Fig.2 is a distribution chart of AR (as received basis) ash of pulverized coal used in boilers in different areas of China. The highest AR ash content of powdered coal used in pulverized coal industrial boilers in China is 34.2% and the lowest AR ash is 5.44%. The AR ash content which is below 15% accounts for 87% of the total coal used. Because of the low ash content of the coal, the thermal efficiency of boiler is relatively high.

![Ash of pulverized coal](image2.png)

Fig.2 Distribution of AR ash of pulverized coal used in boilers in different areas
### 3.3 Analysis of VDAF of coal

Fig. 3 is a distribution chart of VDAF (dry ash-free basis volatiles) of pulverized coal used in boilers in different areas of China. The highest VDAF of powdered coal used in China’s pulverized coal industrial boilers is 33.31% and the lowest VDAF is 20.50%. The VDAF content of all the pulverized coals used is above 20%, and 77% of the used coals have the VDAF content of more than 28%, which are the typical three types of bituminous coal.

![Fig. 3 Distribution of VDAF of pulverized coal used in boilers in different areas](image)

### 3.4 Analysis of total moisture distribution of coal

Fig. 4 shows the total moisture distribution of pulverized coal used in boilers in different areas of China. The total water content of coal-fired industrial boilers in China is 15.5% at most and 4% at least. The proportion of total water below 5% is 57%, and the proportion of total water below 10% is over 90%.

![Fig. 4 Total water distribution of pulverized coal used in boilers in different Areas](image)

### 4. Results and discussion

The quality of pulverized coal used in industrial boilers of China has been analyzed and more than 300 pulverized coal industrial boilers have been involved. Only one of the same type industrial boilers of pulverized coal has been selected for the analysis.
$K_d$ is used to analyze the explosivity of pulverized coal and please see Table 3 for the details. From the table, it can be seen that only 6% of the pulverized coal is of medium explosivity, 15% of the pulverized coal is of high explosivity, and over 78% of the pulverized coal is of extreme explosivity.

Table 3. Relationship between explosivity of pulverized coal and explosion Index $K_d$

| $K_d$ index of pulverized coal | explosivity | Proportion (%) |
|-------------------------------|-------------|----------------|
| $K_d \leq 1.0$                | extreme low explosivity | 0 |
| $1.0 < K_d \leq 3.0$          | low explosivity    | 0 |
| $3.0 < K_d \leq 7.0$          | very low explosivity | 0 |
| $7.0 < K_d \leq 12.0$         | medium explosivity | 6.25 |
| $12.0 < K_d < 17.0$           | high explosivity  | 15.63 |
| $K_d \geq 17.0$               | $IT \leq 680$     | $V_{daf} \geq 25.0$ |

The explosivity of pulverized coal is analyzed by $K_T$, as shown in Table 4. From the table, it can be seen that only 6% of the powdered coal is of medium explosivity, 90% of the powdered coal is of high explosivity, and 3% of the pulverized coal is of extreme explosivity. Comparing Table 3 and Table 4, it is found that the two are different in evaluation of explosion index of powdered coal. $K_T$ and $K_d$ are consistent in evaluation of the medium explosivity of pulverized coal, both accounting for 6.25%. However, in terms of high explosivity, there is a big difference between them, which $K_d$ is 15.63%, and $K_T$ is 90.63%. The main reason for the difference is that $K_T$ takes the influence of moisture and ash into the consideration.

Table 4. Relationship between explosivity of pulverized coal and explosion index $K_T$

| $K_T$ index of pulverized coal | explosivity | Proportion (%) |
|-------------------------------|-------------|----------------|
| $K_T \leq 1.0$                | low         | 0 |
| $1.0 < K_T \leq 1.5$          | medium      | 6.25 |
| $1.5 < K_T \leq 3.5$          | high        | 90.63 |
| $K_T > 3.5$                   | extreme     | 3.12 |

5. Conclusion
This article has comprehensively sorted out the safety regulations and standards for the powder supply and boiler explosion of pulverized coal industrial boilers in China, and selected the powdered coal used in 36 representative boiler models. Through analysis and test, it compares the differences between the explosion index of pulverized coal used in industrial boilers of China and that of Russia. According to the Chinese standard, more than 90% of pulverized coal used in industrial boilers is extremely explosive, but according to the Russian standard, the explosivity of pulverized coal is only high explosive as the influences of moisture and ash are mainly considered in the Russian standard.

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