*Safety Emergency Science*

Research Article

# Influence of the particle size distribution on the explosion severity of coal dust

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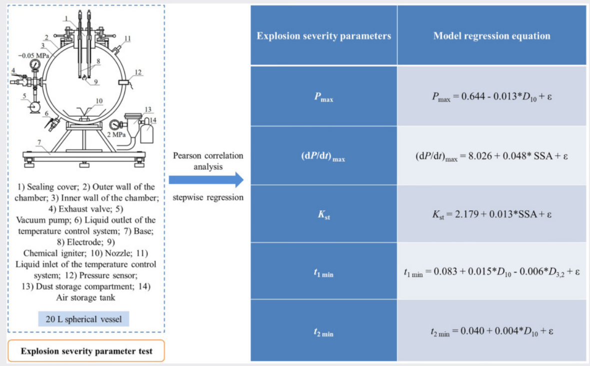
**ABSTRACT:** To precisely identify the critical particle size components affecting coal dust explosions and thereby effectively mitigate explosion risk, this study employed Pearson correlation analysis to statistically examine the relationships between 14 particle size parameters and 5 explosion severity indices. Additionally, stepwise regression was used to identify key particle size parameters affecting coal dust explosion severity, resulting in regression equations for explosion severity indicator models. The results indicate that, according to the Pearson correlation analysis, the particle size parameters with the greatest impact on explosion severity are $D_{10}$, $D_{20}$, $D_{30}$, $D_{3,2}$, and SSA. According to stepwise regression, the particle size parameters that most affect the explosion severity are $D_{10}$, $D_{20}$, $D_{3,2}$, and SSA. Combining both analytical results, the particle size parameters with the greatest influence on explosion severity are $D_{10}$, $D_{20}$, $D_{3,2}$, and SSA. Therefore, when developing explosion prevention and mitigation strategies for coal dust from the perspective of explosion severity, attention should be given to particle size parameters such as $D_{10}$–$D_{30}$, $D_{3,2}$, and SSA.




**KEYWORDS:** particle size distribution; explosion severity; coal dust explosion; Pearson correlation; stepwise regression selection

## 1 Introduction

In recent years, the rapid development of the new energy industry has led to a decreasing trend in coal's share of China's energy consumption structure. However, coal will continue to dominate the country's energy structure in the short term (Wang et al., 2025a; Xu et al., 2025; Zhang et al., 2025). Additionally, the processes of coal mining, processing, and transportation present risks of coal dust explosion (Sahu and Prasad Mishra, 2024; Wang et al., 2023; Wu et al., 2023). Coal dust explosions are characterized by rapid propagation and the instantaneous release of enormous amounts of energy, resulting in high temperatures, high pressure, and severe damage to the surrounding environment. Such explosions can easily trigger chain reactions, escalating the incident scale and often leading to significant casualties (Qian et al., 2023; Tao et al., 2024; Wu et al., 2024; Yu et al., 2023). In both single and multiple explosions, severe damage to nearby facilities is inevitable, and in some cases, these incidents lead to tragic loss of life (Kong et al., 2022; Wang et al., 2025b). Thus, the prevention of coal dust explosions is critical (Cao et al., 2024; Ren et al., 2024; Zhang et al., 2024).

Explosion severity indicators are essential metrics for assessing dust explosion risk (Ren and Zhang, 2022). Typically, dust explosion severity indicators include the maximum explosion pressure ($P_{max}$), the maximum rate of pressure rise ($(dP/dt)_{max}$), and $K_{st}$. The particle size is one of the critical factors affecting the explosion characteristics of coal dust. Liu et al. (2018) studied the impact of the particle size distribution $\sigma_D$ on the explosion characteristics of coal dust and reported that when $D_{50}$ is constant, the maximum explosion pressure and maximum pressure increase rate increase with increasing $\sigma_D$. They also reported a strong correlation between the Sauter mean diameter $D_{3,2}$ and the explosion parameters. Li et al. (2016) examined the effects of the median particle size $D_{50}$ and particle size distribution $\sigma_D$ on coal dust explosion characteristics. The results showed that coal dust with smaller $D_{50}$ and $\sigma_D$ values has higher $P_{max}$ and $(dP/dt)_{max}$ values, indicating more intense explosion reactions.

Researchers have experimentally reported that finer dust particles are more easily ignited, exhibit stronger flame propagation capabilities, and maintain better flame stability (Bagaria et al., 2019). It is generally believed that a critical particle size exists where the dust explosion severity varies significantly on either side of this threshold. This critical particle size is referred to as the characteristic particle size.

The use of average particle size to study dust explosion characteristics is often limited. This study identifies the comprehensive shape of the particle size distribution as a crucial factor, beyond just the median diameter, that cannot be

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overlooked when evaluating ignition susceptibility, flame behavior, and overall explosion violence (Gu et al., 2017). For dust clouds with a broad particle size span, the structure and propagation behavior of explosion flames are significantly modulated by the particle size distribution. Among the parameters, the size fraction with a high mass concentration exerts a dominant influence on the flame characteristics. Reducing the content of critical particle size components that contribute to explosions in coal dust can lower the explosion severity (Zhang et al., 2018). By identifying the critical particle size components affecting coal dust explosion severity, the explosion risk can be reduced by decreasing these components or increasing the proportion of noncombustible components.

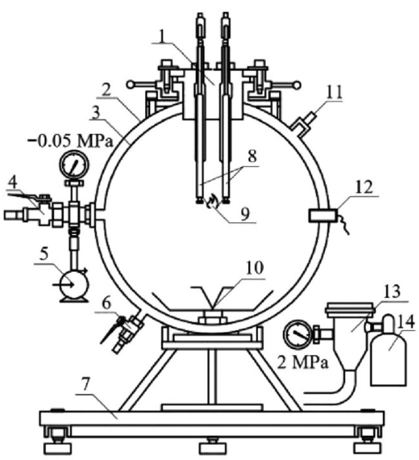
Currently, only the ASTM E2019-03 standard (ASTM, 2019) provides guidance on the use of $D_{4,3}$ or $D_{3,2}$ to characterize particle size for measuring explosion parameters. As a result, the selection of a particle size parameter in explosion testing lacks a solid foundation. This study employs correlation analysis to systematically examine the relationships between 14 particle size parameters ($D_{10}$–$D_{90}$, $D_{3,2}$, $D_{4,3}$, $\sigma_D$, PSS, SSA) and 5 explosion severity indicators ($P_{max}$, $(dP/dt)_{max}$, $K_{st}$, $t_{1\ min}$, and $t_{2\ min}$). The aim of this study was to investigate the influence patterns of different particle size parameters on pulverized coal explosion severity. Furthermore, stepwise regression analysis was used to identify the optimal particle size parameter for characterizing coal dust explosion severity, thereby providing a scientific basis for effective coal dust explosion prevention.

## 2 Materials and methods

Details regarding the particle size distribution representations and the experimental materials are provided in our team's earlier work (Ren et al., 2025).

### 2.1 Experimental methods

The explosion severity index of the dust cloud was tested via a Siwek 20 L spherical vessel manufactured by the Industrial Explosion Protection Institute of Northeastern University, China. The structural details of this apparatus are shown in Fig. 1. The testing system consists of five main parts: a chamber, a control system, a dust dispersion system, an ignition system, and a data acquisition system. The chamber is a standard spherical shape, integrating both a gas storage chamber and a dust storage chamber. The nozzle is designed with an outward-flaring blade structure. The vacuuming and gas-filling processes of the dust storage chamber are automatically executed by the control system. To ensure uniform dust dispersion upon ignition, the internal pressure of the chamber must be maintained at standard atmospheric pressure after ignition.




1) Sealing cover; 2) Outer wall of the chamber; 3) Inner wall of the chamber; 4) Exhaust valve; 5) Vacuum pump; 6) Liquid outlet of the temperature control system; 7) Base; 8) Electrode; 9) Chemical igniters; 10) Nozzle; 11) Liquid inlet of the temperature control system; 12) Pressure sensor; 13) Dust storage chamber; 14) Gas cylinder

**Fig. 1** Siwek 20 L spherical vessel.

The primary indicators involved in the test include the maximum explosion pressure ($P_{max}$), maximum rate of explosion pressure rise ($(dP/dt)_{max}$), explosion index ($K_{st}$), time from ignition to maximum explosion pressure ($t_1$), and time from ignition to maximum rate of explosion pressure rise ($t_2$). These parameters provide critical data for evaluating the explosion characteristics of dust.

On the basis of the ASTM E1226–12a standard (ASTM, 2012), the relevant parameters are precisely defined as follows.

(1) $P_{max}$: The maximum pressure value recorded within the 20 L spherical vessel chamber during a dust explosion experiment, measured in MPa.

(2) $(dP/dt)_{max}$: The maximum rate of explosion pressure rise recorded within the 20 L spherical vessel chamber during a dust explosion experiment, measured in MPa/s.

(3) Explosion index ($K_{st}$): Measured in MPa·m/s, calculated according to Eq. (1):

$$K_{st} = (dP/dt)_{max} V^{\frac{1}{3}} \tag{1}$$

where $V$ is the volume of the explosion chamber. In this study, the volume of the 20 L spherical vessel is 0.02 $m^3$.

(4) $t_d$: Ignition delay time, measured in ms.

(5) $t_1$: The time from the start of ignition to when the pressure within the 20 L spherical vessel reaches its maximum value, measured in ms.

(6) The time from the start of ignition to when the rate of increase in the explosion pressure reaches its maximum value, measured in ms.

The key measurement parameters specified by different standards for measuring explosion severity parameters are shown in Table 1. Compared with the three standards in Table 1, the final selected parameters are an ignition energy of 10 kJ, an initial dust concentration of 250 g/$m^3$, an increment gradient of 250 g/$m^3$, an ignition delay time of 0.06 s, and 3 parallel experiments.

While previous research suggests that ignition energies > 10 kJ may cause overdriving effects, a 10 kJ chemical igniter was deliberately employed in this study to capture the maximum explosion severity parameters of coal dust. In accordance with the GB/T 16426–1996 (GB/T, 1996), ASTM E1226-2013 (ASTM, 2013), and EN 14034-2:2006 (EN, 2006) standards, the key measurement conditions for determining the explosion severity indices were established. The specific parameters are as follows: the ignition energy is set at 10 kJ, and an ignition composition of 0.96 g of zirconium powder, 0.72 g of barium nitrate, and 0.72 g of barium peroxide is used, totaling 2.4 g. Prior to the experiment, the explosion sphere is evacuated to –0.06 MPa, and the gas storage chamber is pressurized to 2.00 MPa. The ignition delay time is set to 0.06 s. To ensure data reliability, each experiment is conducted in triplicate. Under these conditions, the explosion severity indices of coal dust were measured at concentrations of 250, 500, 750, 1 000, and 1 250 g/$m^3$.

The results of the explosion experiments followed the ASTM E1515–14 standard (ASTM, 2014), and Eq. (2) was used to assess the degree of ignition of the dust cloud. An ignition is deemed successful when the pressure ratio $PR$ reaches or exceeds 2.0.

**Table 1** Measurements of the explosion intensity parameters in the GB/T 16426–1996, ASTM E1226-2013, and EN 14034–2: 2006 standards

| Measurement standard | GB/T 16426–1996 | ASTM E1226-2013 | EN 14034-2:2006 |
|---|---|---|---|
| Recommended instrument | 1 $m^3$ cylindrical explosion chamber | 20 L spherical vessel (preferred) | 20 L spherical vessel (alternative) |
| Chemical igniter energy | 10 kJ | Two 5 kJ igniters | Two 5 kJ igniters |
| Dust concentration gradient | — | Initial concentration: 250 g/$m^3$, increment: 250 g/$m^3$ or reduction by 50% | Initial concentration: 250 g/$m^3$, increment: 250 g/$m^3$ or reduction by 50% |
| Ignition delay time | 0.60 s | 0.06±0.005 s | 0.06 s |
| Measurement repetition | — | 3 times | 4 times |

Note: Although the GB/T 16426–1996 standard mentions that a 20 L spherical vessel can be used as an alternative to a 1 $m^3$ cylindrical explosion chamber, it does not specify the corresponding measurement condition parameters. Therefore, only the measurement conditions for the 1 $m^3$ cylindrical explosion chamber are listed in Table 1.

$$PR = \frac{P_{ex} - \Delta P_i}{P_s} \quad (2)$$

where $\Delta P_i$ refers to the increase in internal chamber pressure caused by the ignitor, measured in MPa, and $P_s$ denotes the pressure at the moment of ignition initiation, also measured in MPa.

### 2.2 Stepwise regression methods

Considering the potential multicollinearity among the fourteen particle size parameters, this study employed the condition number method to diagnose multicollinearity. A condition number reaching or exceeding 100 was considered indicative of severe multicollinearity. To address this issue, stepwise regression was subsequently implemented to screen parameters, thereby eliminating those particle size variables with relatively minor effects.

The stepwise regression analysis conducted via SPSS software adopted the "stepwise" mode, with probability thresholds set at 0.05 for entry and 0.051 for removal. All related analyses strictly adhered to these parameter settings. Furthermore, rigorous statistical tests were performed to exclude significant heteroscedasticity, outliers, and influential points, ensuring the robustness of the regression model.

## 3 Results and discussion

### 3.1 Test results

This section investigates the interactions between 14 particle size parameters and 5 explosion severity indicators through correlation analysis, identifying key dust particle size parameters that significantly influence explosion severity. Furthermore, stepwise regression analysis is employed to screen the most representative particle size parameters in dust explosion severity research. The five explosion severity indicators—$P_{max}$, $(dP/dt)_{max}$, $K_{st}$, $t_{1\ min}$, and $t_{2\ min}$—were measured for samples $S_1$–$S_6$ and $B_1$–$B_4$ at different dust concentrations (250, 500, 750, 1000, and 1250 g/$m^3$), and the measurement results are presented in Table 2.

### 3.2 Correlations between coal dust particle size parameters and explosion severity indicators

Table 3 presents the Pearson correlation analysis results between 14 particle size parameters and five explosion severity indicators ($P_{max}$, $(dP/dt)_{max}$, $t_{1\ min}$, $t_{2\ min}$, and $K_{st}$). The analysis indicates a more significant correlation between the particle size parameters and $P_{max}$ and $t_{2\ min}$, with absolute correlation coefficients greater than those with $t_{1\ min}$, $(dP/dt)_{max}$, and $K_{st}$. This suggests that the particle size parameters have a more pronounced effect on $P_{max}$ and $t_{2\ min}$.

According to the Pearson correlation analysis results, polydispersity ($\sigma_D$) has an insignificant effect on the explosion severity and shows inconsistent correlation directions with the explosion severity indicators $P_{max}$, $(dP/dt)_{max}$, $K_{st}$, $t_{1\ min}$, and $t_{2\ min}$. Thus, $\sigma_D$ is preliminarily deemed insufficient to effectively reflect the influence of the particle size distribution on the explosion severity, and excluding this parameter is recommended. Among the remaining 13 particle size parameters, 12 parameters (excluding SSA) are negatively correlated with $P_{max}$, $(dP/dt)_{max}$, and $K_{st}$ and positively correlated with $t_{1\ min}$ and $t_{2\ min}$. In contrast, SSA is inversely correlated with these explosion severity indicators. Specifically, higher values of $P_{max}$, $(dP/dt)_{max}$, and $K_{st}$ or lower values of $t_{1\ min}$ and $t_{2\ min}$ indicate greater explosion severity. With respect to the particle size percentage, coal dust with larger particle sizes tends to have a lower explosion severity.

According to the data presented in Table 3, for the particle size percentile parameters in the range of $D_{10}$–$D_{90}$, the three percentiles most strongly correlated with $P_{max}$, $t_{1\ min}$, and $t_{2\ min}$ are $D_{10}$, $D_{20}$, and $D_{30}$, respectively. In contrast, for $(dP/dt)_{max}$ and $K_{st}$, the most strongly correlated percentiles are $D_{30}$, $D_{20}$, and $D_{10}$. The study results indicate that within the coal dust particle size distribution, smaller particle size components (i.e., the 10th, 20th, and 30th percentiles) are more significantly correlated with $P_{max}$, $(dP/dt)_{max}$, $t_{1\ min}$, $t_{2\ min}$, and $K_{st}$, suggesting that these small particle size fractions have a substantial impact on the explosion severity. Among the parameters $D_{3,2}$, $D_{4,3}$, PSS, and SSA, $D_{3,2}$ has the most prominent correlation with the explosion severity indicators, whereas the PSS has the weakest correlation. Notably, the SSA is significantly correlated with $(dP/dt)_{max}$ and $K_{st}$.

A comprehensive analysis indicates that smaller particle size fractions of coal dust (i.e., the 10th, 20th, and 30th percentiles) are more suitable as particle size characterization methods. The critical particle size parameters relevant to different explosion severity indicators are consistent and are primarily concentrated within coal dust fractions below the 30th percentile. Therefore, in studies of coal dust explosion parameters, it is advisable to select a particle size characterization method that emphasizes the proportion of small particle size fractions within the overall particle size distribution.

### 3.3 Optimal particle size representation for coal dust explosion severity indicators

Given the potential collinearity among the 13 particle size parameters aside from $\sigma_D$, this study employed the condition number method to detect multicollinearity. The analysis results after stepwise regression selection are shown in Table 4. $D_{20}$, $D_{40}$–$D_{90}$, $D_{4,3}$, and PSS were not significantly correlated with the explosion severity indicators and were therefore excluded from further analysis. Among the four retained particle size parameters after variable selection, $D_{10}$ showed a statistically significant correlation with the maximum explosion pressure ($P_{max}$). The SSA also displayed a statistically significant correlation with both $(dP/dt)_{max}$ and $K_{st}$. Both $D_{10}$ and $D_{3,2}$ exhibited statistically

**Table 2** Explosion severity indicators of single and blended coal dust samples at different concentrations

| Explosion severity indicator | Dust concentration/ (g/m$^3$) | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $S_5$ | $S_6$ | $B_1$ | $B_2$ | $B_3$ | $B_4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $P_{ex}$ (MPa) | 250 | 0.603 | 0.522 | 0.425 | 0.286 | 0.272 | 0.104 | 0.576 | 0.582 | 0.393 | 0.604 |
| | 500 | 0.627 | 0.496 | 0.438 | 0.294 | 0.286 | 0.113 | 0.584 | 0.590 | 0.407 | 0.611 |
| | 750 | 0.595 | 0.441 | 0.517 | 0.323 | 0.316 | 0.227 | 0.539 | 0.653 | 0.442 | 0.694 |
| | 1 000 | 0.564 | 0.420 | 0.529 | 0.305 | 0.297 | 0.215 | 0.532 | 0.637 | 0.438 | 0.703 |
| | 1 250 | 0.474 | 0.413 | 0.372 | 0.281 | 0.273 | 0.212 | 0.525 | 0.416 | 0.325 | 0.445 |
| $P_{max}$ (MPa) | — | 0.627 | 0.522 | 0.529 | 0.323 | 0.316 | 0.227 | 0.584 | 0.653 | 0.442 | 0.703 |
| $(dP/dt)_{ex}$ (MPa/s) | 250 | 23.43 | 20.81 | 10.55 | 9.643 | 9.188 | 8.089 | 11.32 | 12.18 | 9.387 | 9.485 |
| | 500 | 43.61 | 32.37 | 14.02 | 10.35 | 9.652 | 9.091 | 16.78 | 19.23 | 13.41 | 11.22 |
| | 750 | 57.36 | 30.24 | 28.85 | 14.14 | 10.83 | 10.81 | 32.91 | 30.01 | 20.25 | 11.66 |
| | 1 000 | 46.71 | 20.50 | 22.74 | 10.83 | 9.874 | 9.734 | 35.02 | 32.10 | 21.83 | 12.91 |
| | 1 250 | 40.36 | 26.43 | 24.63 | 11.27 | 10.14 | 10.01 | 38.77 | 33.52 | 23.28 | 22.52 |
| $(dP/dt)_{max}$ (MPa/s) | — | 57.36 | 32.37 | 28.85 | 14.14 | 10.83 | 10.81 | 38.77 | 33.52 | 23.28 | 22.52 |
| $K_{st}$ (MPa·m/s) | — | 15.57 | 8.787 | 7.831 | 3.838 | 2.940 | 2.934 | 10.52 | 9.099 | 6.319 | 6.113 |
| $t_1$ (s) | 250 | 0.103 | 0.120 | 0.164 | 0.174 | 0.178 | 0.184 | 0.099 | 0.116 | 0.124 | 0.161 |
| | 500 | 0.104 | 0.118 | 0.165 | 0.175 | 0.175 | 0.179 | 0.101 | 0.108 | 0.117 | 0.164 |
| | 750 | 0.107 | 0.124 | 0.171 | 0.178 | 0.176 | 0.182 | 0.097 | 0.113 | 0.159 | 0.169 |
| | 1 000 | 0.098 | 0.162 | 0.173 | 0.177 | 0.181 | 0.186 | 0.071 | 0.100 | 0.165 | 0.116 |
| | 1 250 | 0.093 | 0.158 | 0.169 | 0.180 | 0.177 | 0.190 | 0.068 | 0.075 | 0.097 | 0.113 |
| $t_{1\ min}$ (s) | — | 0.093 | 0.118 | 0.164 | 0.174 | 0.175 | 0.179 | 0.068 | 0.075 | 0.097 | 0.113 |
| $t_2$ (s) | 250 | 0.084 | 0.074 | 0.088 | 0.153 | 0.155 | 0.157 | 0.083 | 0.091 | 0.101 | 0.116 |
| | 500 | 0.055 | 0.071 | 0.086 | 0.149 | 0.153 | 0.154 | 0.081 | 0.087 | 0.092 | 0.118 |
| | 750 | 0.066 | 0.100 | 0.107 | 0.146 | 0.150 | 0.153 | 0.072 | 0.089 | 0.108 | 0.123 |
| | 1 000 | 0.072 | 0.125 | 0.134 | 0.145 | 0.152 | 0.156 | 0.028 | 0.082 | 0.112 | 0.092 |
| | 1 250 | 0.069 | 0.117 | 0.120 | 0.142 | 0.151 | 0.162 | 0.022 | 0.051 | 0.080 | 0.089 |
| $t_{2\ min}$ (s) | — | 0.055 | 0.071 | 0.086 | 0.145 | 0.150 | 0.153 | 0.022 | 0.051 | 0.080 | 0.089 |

significant correlations with $t_{1\ min}$. $D_{10}$'s correlation with $t_{2\ min}$ was also statistically significant. Table 5 presents the adjusted $R^2$ values and the $p$ values of the F test for the stepwise regression-selected model, while the regression equations for the coal dust explosion severity indicators are shown in Table 6.

Studies have indicated that the particle size percentile $D_{10}$ has a relatively significant correlation with the primary explosion severity indicator $P_{max}$. Specifically, the correlation of $D_{10}$ passed the t test with a $p$ value of 0.001, a level of significance indicating a statistically significant relationship between smaller particle size percentiles and $P_{max}$. Thus, the fine particle size fractions are key factors in determining the maximum explosion pressure.

For the indicators $(dP/dt)_{max}$ and $K_{st}$, since $K_{st}$ is derived from $(dP/dt)_{max}$ by multiplying it by the cube root of the chamber volume, the stepwise regression analysis of the particle size parameters as independent variables for these two dependent variables yielded consistent results. Among the nine particle size percentiles selected in this study, none exhibited statistically significant correlations with either indicator, and among the remaining particle size parameters, only the SSA exhibited a statistically significant correlation. Therefore, the SSA is an important particle size parameter for evaluating the values of the dependent variables $(dP/dt)_{max}$ and $K_{st}$.

Among the 14 particle size parameters selected in this study, only a few parameters showed statistically significant correlations with the dependent variables $t_{1\ min}$ and $t_{2\ min}$. Both $D_{10}$ and $D_{3,2}$ showed statistically significant correlations with $t_{1\ min}$, with t test $p$ values of 0.003 and 0.011, respectively, whereas $D_{10}$ had a statistically significant correlation with $t_{2\ min}$, with a t test $p$ value of $3.7\times10^{-4}$. The propensity of coal dust to trigger secondary explosions was observed in the testing process of this study. The occurrence of secondary explosions may significantly interfere with the dependent variables, a factor that should be considered during statistical analysis. Even after accounting for this interference, the same conclusion remains valid: smaller particle size percentiles are critical parameters for accurately reflecting the impact of the particle size distribution on the rate of increase in the explosion pressure.

As shown in Table 6, the particle size parameters with the greatest impact on explosion severity are primarily the small particle size ($D_{10}$–$D_{30}$) and SSA. This can be attributed to two main reasons. On the one hand, the small particle size of coal dust results in a high specific surface area and greater porosity of the coal particles, providing a broad diffusion pathway for oxygen, which facilitates the reaction. As a result, the explosion reaction becomes more intense when it occurs (Huéscar Medina et al., 2015). On the other hand, when the dust particle size is sufficiently small, the electrostatic forces between fine particles become unusually prominent, causing small particles to easily aggregate into clumps, which, in turn, may inhibit the occurrence of an explosion (Choi et al., 2001; Eckhoff, 2012).

The results of this study align with previous research findings, confirming that fine particle size fractions are the key components influencing explosion severity (Liu et al., 2018). Therefore, during the prevention of explosion accidents, attention should be focused on particle size parameters such as $D_{10}$–$D_{30}$, $D_{3,2}$, and SSA.

### 3.4 Discussion of influencing mechanisms

A smaller particle size has a more pronounced effect on $P_{max}$. Coarser particles may not fully combust after the flame front passes or may not ignite in time. This unburned fuel is expelled

**Table 3** Pearson correlation coefficients between coal particle size parameters and explosion severity indicators

| Particle size parameter | | Explosion severity indicator | | | | |
|---|---|---|---|---|---|---|
| | | $P_{max}$ | $(dP/dt)_{max}$ | $K_{st}$ | $t_{1\ min}$ | $t_{2\ min}$ |
| $D_{10}$ | Pearson correlation coefficient | −0.867** | −0.797** | −0.797** | 0.840** | 0.901** |
| | Significance | 0.001 | 0.006 | 0.006 | 0.002 | $3.7\times10^{-4}$ |
| $D_{20}$ | Pearson correlation coefficient | −0.824** | −0.803** | −0.803** | 0.814** | 0.893** |
| | Significance | 0.003 | 0.005 | 0.005 | 0.004 | 0.001 |
| $D_{30}$ | Pearson correlation coefficient | −0.802** | −0.804** | −0.804** | 0.776** | 0.870** |
| | Significance | 0.005 | 0.005 | 0.005 | 0.008 | 0.001 |
| $D_{40}$ | Pearson correlation coefficient | −0.743* | −0.774** | −0.774** | 0.678* | 0.796* |
| | Significance | 0.014 | 0.009 | 0.009 | 0.031 | 0.006 |
| $D_{50}$ | Pearson correlation coefficient | −0.715* | −0.750* | −0.750* | 0.623 | 0.750* |
| | Significance | 0.020 | 0.012 | 0.012 | 0.054 | 0.013 |
| $D_{60}$ | Pearson correlation coefficient | −0.691* | −0.728* | −0.728* | 0.588 | 0.719* |
| | Significance | 0.027 | 0.017 | 0.017 | 0.074 | 0.019 |
| $D_{70}$ | Pearson correlation coefficient | −0.673* | −0.710* | −0.710* | 0.560 | 0.695* |
| | Significance | 0.033 | 0.021 | 0.021 | 0.092 | 0.026 |
| $D_{80}$ | Pearson correlation coefficient | −0.658* | −0.699* | −0.699* | 0.534 | 0.676* |
| | Significance | 0.038 | 0.025 | 0.025 | 0.112 | 0.032 |
| $D_{90}$ | Pearson correlation coefficient | −0.644* | −0.709* | −0.709* | 0.501 | 0.662* |
| | Significance | 0.045 | 0.022 | 0.022 | 0.140 | 0.037 |
| $D_{3,2}$ | Pearson correlation coefficient | −0.836** | −0.791** | −0.791** | 0.768** | 0.860** |
| | Significance | 0.003 | 0.006 | 0.006 | 0.009 | 0.001 |
| $D_{4,3}$ | Pearson correlation coefficient | −0.701* | −0.750* | −0.750* | 0.581 | 0.728* |
| | Significance | 0.024 | 0.013 | 0.013 | 0.078 | 0.017 |
| $\sigma_D$ | Pearson correlation coefficient | 0.087 | −0.240 | −0.240 | −0.372 | −0.152 |
| | Significance | 0.810 | 0.505 | 0.505 | 0.290 | 0.675 |
| PSS | Pearson correlation coefficient | −0.346 | −0.620 | −0.620 | 0.039 | 0.329 |
| | Significance | 0.328 | 0.560 | 0.560 | 0.915 | 0.354 |
| SSA | Pearson correlation coefficient | 0.628 | 0.965** | 0.965** | −0.656* | −0.721* |
| | Significance | 0.052 | $6.0\times10^{-6}$ | $6.0\times10^{-6}$ | 0.040 | 0.019 |

Note: (1) "**" indicates that the correlation is significant at the 0.01 level (two-tailed); (2) "*" indicates that the correlation is significant at the 0.05 level (two-tailed).

**Table 4** *p* values of the t tests for the coal dust particle size parameters and explosion severity parameters after stepwise regression selection

| Particle size parameter | *p* value of the t test | | | | |
|---|---|---|---|---|---|
| | $P_{max}$ | $(dP/dt)_{max}$ | $K_{st}$ | $t_{1\ min}$ | $t_{2\ min}$ |
| $D_{10}$ | 0.001 | — | — | 0.003 | $3.7\times10^{-4}$ |
| $D_{3,2}$ | — | — | — | 0.011 | — |
| SSA | — | $6.0\times10^{-6}$ | $6.0\times10^{-6}$ | — | — |

**Table 5** Adjusted $R^2$ values and *p* values of the F test for the stepwise regression model of explosion severity

| | Model dependent variable | | | | |
|---|---|---|---|---|---|
| | $P_{max}$ | $(dP/dt)_{max}$ | $K_{st}$ | $t_{1\ min}$ | $t_{2\ min}$ |
| Adjusted $R^2$ | 0.720 | 0.922 | 0.922 | 0.858 | 0.789 |
| *p* value of the F test | 0.001 | $6.0\times10^{-6}$ | $6.0\times10^{-6}$ | $4.5\times10^{-4}$ | $3.7\times10^{-4}$ |

from the reaction zone with the explosion products, resulting in energy loss. In contrast, finer particles can almost entirely participate in the reaction, maximizing the conversion of chemical energy into thermal energy. $P_{max}$ essentially represents the ideal pressure achieved under the assumption that all fuel combusts completely and instantaneously at a constant volume. Finer particles more closely approximate this ideal scenario. Therefore, at the optimal stoichiometric concentration, a system of finer particles achieves a higher "combustion efficiency", thereby releasing more total energy and resulting in a higher $P_{max}$.

SSA has a more pronounced effect on $(dP/dt)_{max}$ and $K_{st}$. A larger specific surface area results in a shorter particle heating time and pyrolysis/gasification time. Fine particles can be heated to the ignition point almost instantaneously and release combustible gases (or undergo direct surface combustion). This leads to a sharp increase in the flame propagation speed. A faster flame means that more fuel is ignited per unit time, resulting in a higher energy release rate (power). For solid particles, combustion reactions primarily occur on the surface. The reaction rate is proportional to the available surface area. According to the

**Table 6** Regression equation for the model of the explosion severity parameters

| Explosion severity parameter | Model regression equation |
|---|---|
| $P_{max}$ | $P_{max} = 0.644 - 0.013D_{10} + \varepsilon$ |
| $(dP/dt)_{max}$ | $(dP/dt)_{max} = 8.026 + 0.048SSA + \varepsilon$ |
| $K_{st}$ | $K_{st} = 2.179 + 0.013SSA + \varepsilon$ |
| $t_{1\,min}$ | $t_{1\,min} = 0.083 + 0.015D_{10} - 0.006D_{3,2} + \varepsilon$ |
| $t_{2\,min}$ | $t_{2\,min} = 0.040 + 0.004D_{10} + \varepsilon$ |

Arrhenius law, the reaction rate constant is $k = A\exp(-Ea/(RT))$. An increase in the specific surface area effectively significantly increases the preexponential factor $A$ (a constant related to the frequency of reactant collisions). More surface active sites mean more opportunities for "reactive collisions". Therefore, an increase in the specific surface area directly and significantly enhances the overall apparent reaction rate. As shown in formula ($x$), the effects of the SSA on $K_{st}$ and $(dP/dt)_{max}$ should be consistent.

## 4 Conclusions

This study applied Pearson correlation analysis to examine the relationships between 14 particle size parameters ($D_{10}$–$D_{90}$, $D_{3,2}$, $D_{4,3}$, $\sigma_D$, PSS, SSA) and five explosion severity parameters ($P_{max}$, $(dP/dt)_{max}$, $K_{st}$, $t_{1\,min}$, and $t_{2\,min}$), and analyzed the impact of different particle size parameters on the explosion severity of coal dust. Stepwise regression selection was used to identify the optimal particle size representation parameters that influence coal dust explosion severity. The main conclusions are as follows:

(1) The results of the Pearson correlation analysis revealed that the particle size percentiles $D_{10}$, $D_{20}$, and $D_{30}$ were most significantly correlated with the explosion intensity indicators. Among the parameters $D_{3,2}$, $D_{4,3}$, PSS, and SSA, $D_{3,2}$ exhibits the most prominent correlation with the explosion intensity indicators, whereas PSS has a relatively low correlation. The SSA, however, shows a strong correlation with $(dP/dt)_{max}$ and $K_{st}$.

(2) The results of the stepwise regression selection method indicate that, statistically, the particle size parameter $D_{10}$ is significantly correlated with $P_{max}$. The SSA also has statistically significant correlations with $(dP/dt)_{max}$ and $K_{st}$. The particle size parameters $D_{10}$ and $D_{3,2}$ both exhibit statistically significant correlations with $t_{1\,min}$. $D_{10}$'s correlation with the $t_{2\,min}$ value is also statistically significant.

(3) A comprehensive analysis indicates that fine particle size fractions are the key components influencing the maximum explosion pressure, whereas the SSA is an important particle size parameter for evaluating the dependent variables $(dP/dt)_{max}$ and $K_{st}$. Therefore, during the prevention of explosion accidents, attention should be focused on particle size parameters such as $D_{10}$–$D_{30}$, $D_{3,2}$, and SSA.

Future research could consider conducting explosion index tests on several key particle size parameters influencing explosion severity via a controlled variable method. Specifically, different samples should be prepared such that, in addition to the target particle size variables, all other influencing factors remain as consistent as possible. This approach requires many experiments for screening, and although the process is complex, it yields highly reliable results. The focus should be on assessing the relative contributions of these key particle size parameters to explosion severity, thereby providing a more robust understanding of the relationship between particle size and explosion intensity. Moreover, it should be emphasized that the findings of this study are specifically relevant to bituminous coal with comparable industrial analysis. The conclusions can only serve as a reference for other coal types whose explosion characteristics require separate investigation.

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## Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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