THERMODYNAMICS OF THE COAL DUST EXPLOSION
Main Factors and Optimal Control

by

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The explosion intensity and the low explosion limit of the coal dust explosion are affected by the calorific value and the heat transfer rate of the coal dust, which are closely related to the coal quality index. This paper studies experimentally the low explosive limit of the coal dust with different coal quality indexes. Based on the principal component analysis, the main factors affecting the low explosive limit are obtained by extracting the principal components from the coal quality indexes. Through comparative analysis, a regression model is proposed to predict the low explosive limit for practical applications.

Key words: *coal dust explosion, heat conduction equation, principal component analysis, low explosive limit, coal quality index*

Introduction

A coal dust explosion is a major hidden danger in the process of coal mining [1]. The low explosion limit (LEL) of combustible dust is the main parameter to characterize the combustible and explosive risk of the dust [2-4]. Chawla *et al.* [5] conducted a dust explosion experiment with a 20 L spherical airtight container, and measured the effect of the ignition energy on the LEL of the coal dust from different producing areas. The results showed that the LEL decreased with the increase of the ignition energy. He and Zhang [6] pointed out that the LEL of the coal dust decreased with the increase of its volatile content. When the volatile content was reduced to a certain value, the LEL tended to a limit. In a 3.2 L combustion pipeline, Liu *et al.* [7] conducted that the LEL was significantly reduced by increasing the volume fraction of methane in the mixture of methane and coal dust. Li [8] pointed out that the LEL decreased exponentially with the increase of the gas concentration. He [9] gave an analytical method for thermal instability. The quantitative research on the influence of coal dust compositions on the LEL was relatively few, and the understanding of the mechanism of the coal dust explosion was too simple to be practically used. In this paper, the LEL of the coal dust with different coal components is studied using a 20 L spherical explosion test system. The effects of the volatile component, the moisture content, the fixed carbon content, and the ash content on the LEL are analyzed. Based on the principal component analysis, the principal component extraction of coal quality indexes affecting the LEL is carried out, and the main factors influencing the LEL and the regression model of predicting the LEL are obtained.

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Experimental system

Experimental sample

Fourteen types of coals were crushed, and particle sizes less than 75 mm were sieved for test in this experiment. The industrial analysis of the coal samples was shown in tab. 1.

Table 1. Industrial analysis of fourteen different coal dusts

Coal sample number	M_{ad} [%]	A_{ad} [%]	V_{ad} [%]	F_{Cad} [%]	A_d [%]	V_d [%]	V_{daf} [%]	F_{Cd} [%]
1#	1.04	10.02	20.78	68.16	10.13	21.00	23.36	68.87
2#	1.51	21.27	24.72	52.50	21.60	25.10	32.01	53.30
3#	1.14	14.75	21.81	62.30	14.92	22.06	25.93	63.02
4#	1.08	8.07	19.40	71.45	8.16	19.61	21.35	72.23
5#	4.35	41.55	22.59	31.51	43.44	23.62	41.76	32.94
6#	1.71	16.42	28.38	53.49	16.70	28.87	34.66	54.43
7#	0.94	19.89	25.11	54.06	20.08	25.35	31.72	54.57
8#	1.63	44.10	20.25	34.02	44.83	20.59	37.31	34.58
9#	1.06	14.23	21.70	63.01	14.39	21.93	25.62	63.68
10#	1.22	11.68	28.00	59.10	11.82	28.35	32.15	59.83
11#	0.85	14.95	28.31	55.89	15.08	28.55	33.62	56.37
12#	1.18	9.77	20.68	68.37	9.89	20.93	23.22	69.18
13#	1.25	13.1	27.34	58.31	13.26	27.69	31.92	59.05
14#	1.48	43.03	19.62	35.87	43.67	19.91	35.36	36.42

where M_{ad} is the moisture on air dry basis, A_{ad} – the ash on air dry basis, V_{ad} – the volatile on air dry basis, F_{Cad} – the carbon content on air dry basis, A_d – the ash on dry basis, V_d – the volatile on dry basis, V_{daf} – the volatile on dry ash-free basis, and F_{Cd} – the carbon content on dry basis

Experimental equipment and methods

The structure of the 20 L spherical explosion test system is shown in fig. 1. The device body is mainly composed of a double-layer stainless steel ball with a volume of 20 L, a dust

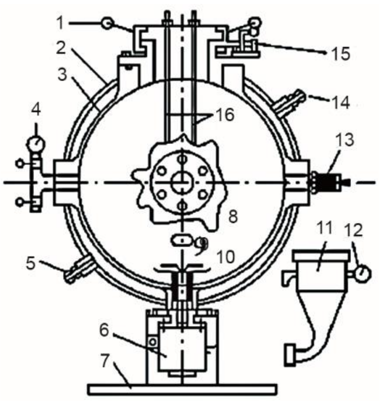

Figure 1. The 20 L spherical vessels for explosion test; *1 – sealed cap, 2 – outer jacket, 3 – inner jacket, 4 – vacuum meter, 5 – circulation water inlet, 6 – mechanical two-way valve, 7 – pedestal, 8 – sightglass, 9 – vacuum orifice, 10 – scattered valve, 11 – dust container, 12 – electro connecting pressure gauge, 13 – pressure sensor, 14 – circulation water outlet, 15 – safety and limit switches, 16 – ignition rod*

tank with a volume of 0.6 L and a gas distribution system. First, a certain amount of coal dust is put into the dust tank, and is pressurized to 2 MPa by filling a high pressure air. Then, the coal dust is ejected from the coal dust tank to the ball through the dispersion nozzle, and a highly turbulent coal dust cloud is formed. A 10 kJ chemical igniter made of zirconium powder, barium nitrate, and barium peroxide with a mass ratio of 4:3:3 is used in the experiment.

Results and analysis

Analysis of influence factors of the lower explosion limit of fourteen kinds of the coal dust

The LEL values of 14 kinds of coal dusts were measured by the test, tab. 2.

Table 2. Lower explosive limit of fourteen different coal dusts

Coal sample number	1#	2#	3#	4#	5#	6#	7#
LEL [gm^{-3}]	75	125	95	90	80	60	65
Coal sample number	8#	9#	10#	11#	12#	13#	14#
LEL [gm^{-3}]	120	115	70	70	75	70	130

The explosion process of the coal dust generally contains two reaction processes: the homogeneous combustion of precipitated volatile gases and the heterogeneous combustion of solid carbon, which play a vital role in the overall reaction rate of the coal dust. In the heating/cooling process of coal, the heat conduction equation can be written as [10]:

$$\frac{\partial T}{\partial t}=\frac{\lambda}{\rho C_p}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right) \quad (0<r<R) \tag{1}$$

Boundary conditions:

$$\frac{\partial T}{\partial r}+\frac{\alpha}{\lambda}(T-T_0)=0 \quad (r=R, \quad t>0), \quad T=T_a \quad (r>R, \quad t\geq 0)$$

The relationship between the specific heat capacity, C_p, of loose coal samples and V_{daf} can be expressed [11]:

$$\begin{aligned} C_p &= 1.86V_{\text{daf}}+802.4 \quad (30\,^\circ\text{C}) \\ C_p &= 3.62V_{\text{daf}}+1100.0 \quad (60\,^\circ\text{C}) \end{aligned} \tag{2}$$

It can be seen that the quality index of coal is an important factor affecting its heat transfer rate from the previous two formulas. As shown in figs. 2 and 3, the LEL of the coal dust tends to decline with the increase of V_{ad} and F_{Cad}. The V_{ad} of coal samples 1, 3, 4, and 8 are all around 20%. As can be seen from the fig. 4, with the increase of M_{ad}, the LEL of the coal dust has an increase tendency, this is because the presence of water will reduce the combustible qualitative content in the fuel, so as to reduce the calorific value of fuel. In the process of fuel combustion, the heat release rate of fuel combustion also decreases due to the absorption of heat by water evaporation. As shown in fig. 5, with the increase of A_{ad}, the LEL of the coal dust tends to increase. In the process of the coal dust explosion, the coal ash absorbs a certain amount of heat and reduces the contact area between combustible materials and oxygen, thus reducing the heat release rate of the coal dust explosion.

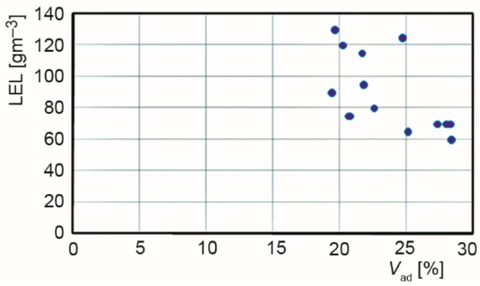

Figure 2. Evolutions of LEL with V_{ad} for fourteen kinds of coal dusts

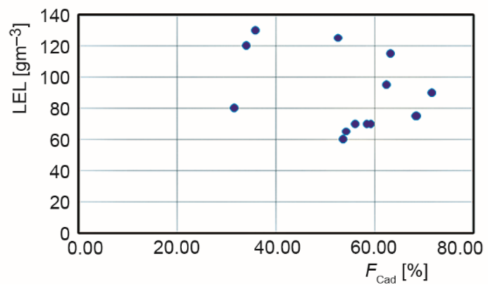

Figure 3. Evolutions of LEL with F_{cad} for kinds of coal dusts

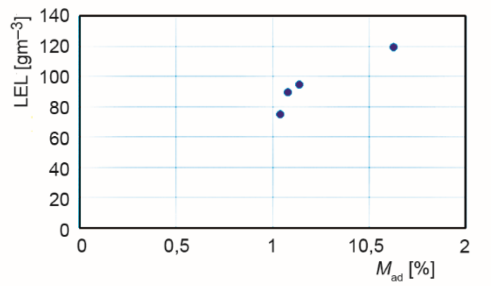

Figure 4. Evolutions of LEL with M_{ad} for 1#, 3#, 4#, 8# coal dusts

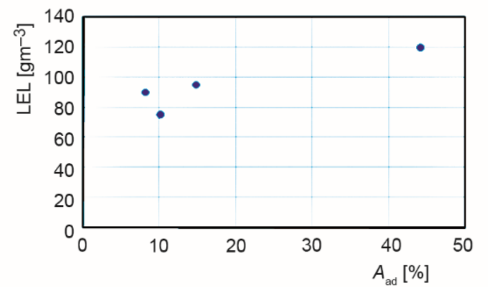

Figure 5. Evolutions of LEL with A_{ad} for 1#, 3#, 4#, 8# coal dusts

Principal component analysis of factors affecting the lower explosive limit of coal dust

In order to analyze the problem comprehensively, eight coal quality indexes are selected in this paper, which are M_{ad}, X_1, A_{ad}, X_2, V_{ad}, X_3, F_{Cad}, X_4, A_d, X_5, V_d, X_6, V_{daf}, X_7, and F_{Cd}, X_8. Based on the industrial analysis of 14 coal samples, the observation matrix of the eight coal quality indexes of these coal samples can be obtained, noted as X, which is a matrix with 14 rows representing fourteen different coal samples and 8 columns representing eight coal quality indexes. The k^{th} column of X is denoted as $X_k (k = 1, 2, \cdots, 8)$. The Y is a vector composed of LEL of 14 coal samples. The correlation coefficients are shown in tab. 3.

It can be seen from tab. 3 that the autocorrelation coefficient of some coal quality indexes reaches 1000, which indicates that they have serious autocorrelation and will lead to the information provided by coal quality index data to some extent overlap. In this paper, the principal component analysis is used to eliminate autocorrelation and reduce the dimension of the data. The correlation coefficients of Y and X_k are mostly greater than 0.3, indicating that they have a certain correlation. So it is suitable for analyzing the influence of the coal quality index on LEL. Because the principal component analysis can weaken the correlation between

Table 3. Table of the correlation coefficient

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	Y
X_1	1.000	0.607	–0.075	–0.656	0.625	–0.014	0.645	–0.643	0.016
X_2	0.607	1.000	–0.295	–0.964	1.000	–0.260	0.776	–0.965	0.526
X_3	–0.075	–0.295	1.000	0.034	–0.293	0.998	0.358	0.035	–0.580
X_4	–0.656	–0.964	0.034	1.000	–0.965	–0.004	–0.915	1.000	–0.374
X_5	0.625	1.000	–0.293	–0.965	1.000	–0.257	0.779	–0.966	0.518
X_6	–0.014	–0.260	0.998	–0.004	–0.257	1.000	0.398	–0.003	–0.581
X_7	0.645	0.776	0.358	–0.915	0.779	0.398	1.000	–0.914	0.072
X_8	–0.643	–0.965	0.035	1.000	–0.966	–0.003	–0.914	1.000	–0.379
Y	0.016	0.526	–0.580	–0.374	0.518	–0.581	0.072	–0.379	1.000

independent variables in regression analysis, we extract principal components from the covariance matrix of standardized sample data, that is, from the sample correlation matrix **R**, which can be obtained by the observation matrix X, and the principal components of eight coal quality indexes which affect the LEL of the coal dust can be extracted from **R**. As shown in tab. 4.

$$\mathrm{R} = \begin{bmatrix} 1.000 & 0.607 & -0.075 & -0.656 & 0.625 & -0.014 & 0.645 & -0.643 \\ 0.607 & 1.000 & -0.295 & -0.964 & 1.000 & -0.260 & 0.776 & -0.965 \\ -0.075 & -0.295 & 1.000 & 0.034 & -0.293 & 0.998 & 0.358 & 0.035 \\ -0.656 & -0.964 & 0.034 & 1.000 & -0.965 & -0.004 & -0.915 & 1.000 \\ 0.625 & 1.000 & -0.293 & -0.965 & 1.000 & -0.257 & 0.779 & -0.966 \\ -0.014 & -0.260 & 0.998 & -0.004 & -0.257 & 1.000 & 0.398 & -0.003 \\ 0.645 & 0.776 & 0.358 & -0.915 & 0.779 & 0.398 & 1.000 & -0.914 \\ -0.643 & -0.965 & 0.035 & 1.000 & -0.966 & -0.003 & -0.914 & 1.000 \end{bmatrix}$$

Table 4. Result of principal component analysis

Principal component	Eigenvalue	Variance contribution rate [%]	Accumulating contribution rate [%]
F_1	5.193	64.918	64.918
F_2	2.278	28.472	93.39

From tab. 4, it can be seen that F_1 and F_2 can reflect the information of 93.39% provided by the coal quality indexes. Therefore, F_1 and F_2 are regarded as the principal components affecting the LEL of the coal dust. The coefficients of standardized variables in F_1 and F_2 are shown in tab. 5.

Table 5. Unit orthogonal eigenvectors

Standardized variable	x_1^*	x_2^*	x_3^*	x_4^*	x_5^*	x_6^*	x_7^*	x_8^*
x_1^*	0.0618	0.0819	–0.0088	–0.0838	0.0822	–0.0051	0.0752	–0.0837
x_2^*	0.0091	–0.0586	0.2890	–0.0187	–0.0578	0.2903	0.1317	–0.0184

From tab. 5, F_1 and F_2 can be expressed:

$$F_1 = 0.0618x_1^* + 0.0819x_2^* - 0.0088x_3^* - 0.0838x_4^* + 0.0822x_5^* - \\ -0.0051x_6^* + 0.0752x_7^* - 0.0837x_8^* \quad (3)$$

$$F_2 = 0.091^*_{x1} - 0.0586^*_{x2} + 0.289^*_{x3} - 0.0187^*_{x4} - 0.0578^*_{x5} + 0.2903^*_{x6} + 0.1317^*_{x7} - 0.0184^*_{x8} \quad (4)$$

From eqs. (3) and (4), we can see that the carbon content, the ash content and the volatile component are the main factors affecting the LEL of the coal. The principal component regression establishes three regression models to eliminate the co-linearity of the standardized variables. The significance index of model 3 is 0.006, the correlation index is 0.834, and the data error is small. It can be used as a prediction model for the coal dust's LEL. According to model 3, the equation:

$$Y = 105.074 + 58.875F_1 - 92307F_1^2 - 35.043F_2 \quad (5)$$

is selected to fit the data. The 1# -14 # coal dust LEL prediction value is calculated, and its error is compared with the experimental value, as shown in tab. 6.

Table 6. The predicted value of the LEL of 1# - 14# coal dusts

Coal sample number	1#	2#	3#	4#	5#	6#	7#
Calculated value [gm^{-3}]	85	100	98	82	79	72	93
Error	–10	25	–3	12	1	–12	–28
Coal sample number	8#	9#	10#	11#	12#	13#	14#
Calculated value [gm^{-3}]	121	97	61	66	86	68	131
Error	–1	18	11	4	–9	2	1

To verify the reliability of the model, five other kinds of pulverized coal are selected for the test. The industrial analysis, the LEL and the predicted value of the LEL calculated by model 3 of these coal samples are shown in tab. 7. It can be seen that the predicted values of the LEL of 1# -19# coal dust are basically consistent with the experimental values, and the errors are within the acceptable range, indicating that the prediction of the LEL of the coal dust by model 3 is reliable.

Table 7. Industrial analysis, LEL and its predicted value of 15# - 19# coal dusts

Coal sample number	M_{ad} [%]	A_{ad} [%]	V_{ad} [%]	F_{Cad} [%]	A_d [%]	V_d [%]	V_{daf} [%]	F_{Cd} [%]	LEL [gm^{-3}]	Predicted value [gm^{-3}]
15#	8.36	12.71	37.31	41.62	13.87	40.71	47.27	45.42	85	89.0438
16#	2.68	3.94	40.98	52.4	4.05	42.11	43.89	53.84	60	67.1930
17#	1.31	65.27	18.71	14.71	66.14	18.96	55.98	14.90	135	128.1075
18#	1.08	8.07	19.40	71.45	8.16	19.61	21.35	72.23	90	90.2257
19#	4.05	12.07	30.33	53.55	12.58	31.61	36.16	55.81	100	94.8701

Conclusions

This paper conducts an experimental study on the coal dust LEL with different coal quality indexes, and analyzes the influence of the volatile components, the moisture, the carbon content and the ash content on LEL. The LEL of the coal dust tends to increase with the increase of the ash and the moisture contents, and it decreases with the increase of the volatile component and the carbon content. Based on the principal component analysis, the principal components are extracted from coal quality indexes, and the main factors affecting the LEL of the coal dust are obtained. A reliable regression model is obtained to predict the LEL of the coal dust with different coal quality indexes. Additionally, an optimization problem for the LEL can be quickly established and solved, and the thermal instability [9] and the thermal oscillation [12-14] are two future topics.

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References

[1] Masto, R. E., *et al.*, Impacts of Opencast Coal Mine and Mine Fire on the Trace Elements' Content of the Surrounding Soil Vis-a-Vis Human Health Risk, *Toxicological & Environmental Chemistry Reviews, 93* (2011), 2, pp. 223-237
[2] Ban, T., *et al.*, Effect of Ignition Energy on Coal Dust Explosion, *Thermal Science, 24* (2020), 4, pp. 2621-2628
[3] Ban, T., Cui, R. Q., He's Homotopy Perturbation Method for Solving Time Fractional Swift-Hohenberg Equations, *Thermal Science, 22* (2018), 4, pp. 1601-1605
[4] Zhao, P., *et al.*, Minimum Explosion Concentration of Coal Dusts in Air with Small Amount of CH_4/H_2/CO under 10-kJ Ignition Energy Conditions, *Fuel, 260* (2020), Jan., 116401
[5] Chawla, N., *et al.*, A Comparison of Experiment Methods to Determine the Minimum Explosible Concentration of Dusts, *Fuel, 75* (1996), 6, pp. 654-658
[6] He, C. Y., Zhang, Y. H., The Relationship between Coal Dust Explosion Characteristics and Volatile Components, *Industrial Safety and Dust Control, 11* (1997), 1, pp. 24-27
[7] Liu, Y., *et al.*, On Lower Limit of Explosive Coal Dust in Coal Dust Mixture with Methane, *Journal of Safety and Environment, 7* (2007), 2, pp. 129-131
[8] Li, R. Z., Minimum Explosive Concentration of Coal Dust Cloud in the Coexistence of Gas and Coal Dust, *Explosion and Shock Waves, 38* (2018), 4, pp. 913-917
[9] He, J. H., Maximal Thermo-geometric Parameter in a Nonlinear Heat Conduction Equation, *Bulletin of the Malaysian Mathematical Sciences Society, 39* (2016), 2, pp. 605-608
[10] Zhang, S. Y., Xie A. G., Two Dimensional Numerical Simulations of Thermal Processes in a Coke Oven Chamber, *Energy for Metallurgical Industry, 32* (2013), 1, pp. 20-25
[11] Song, N., *et al.*, The Heat Capacity Test and Analysis of Loose Coal in Low Temperature, *Energy Technology and Manageme, 27* (2011), 2, pp. 94-96
[12] Liu, F. J., *et al.*, Thermal Oscillation Arising in a Heat Shock of a Porous Hierarchy and its Application, *Facta Universitatis Series: Mechanical Engineering*, On-line first, https://doi.org/10.22190/FUME210317054L, 2021
[13] Ban, T., *et al.*, Principal Component Analysis of the Effect of Coal Quality Indexes on the Maximum Explosion Pressure of Coal Dust, *Thermal science, 25* (2021), 3B, pp. 2183-2189
[14] Ban, T., Chen, C. P., New Inequalities for the Volume of the Unit Ball in R^n, *Journal of Mathematical Inequalities, 11* (2017), 2, pp. 527-542

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