PRINCIPAL COMPONENT ANALYSIS OF THE EFFECT OF COAL QUALITY INDEXES ON THE MAXIMUM EXPLOSION PRESSURE OF COAL DUST

by

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It is well-known that the calorific value and heat transfer speed of coal are closely related to the coal quality index, and affect the explosion intensity and the maximum explosion pressure of coal dust explosion. In this paper, the pressure for different coal quality indexes is studied experimentally, and the main parameters affecting the pressure are elucidated by the principal component analysis of multivariate statistical analysis.

Key words: *coal dust explosion, maximum explosion pressure, coal quality index, principal component analysis*

Introduction

Coal dust explosions and flash fires are a major safety concern in coal mines and extractive industries [1, 2]. Coal dust in a cloud form is assumed to be homogenous, and it can be ignited when a sufficient ignition energy is provided [3-7]. In order to evaluate and prevent coal dust explosion, we should determine the main parameters affecting the minimal ignition temperature of a cloud, the lower explosive limit, the maximal explosion pressure (MEP), the maximal rate of pressure rise, and the explosion index. Though there was much literature on the study, many researches focused on the study of the effects of a single or few parameter on explosions, such as coal dust concentration, particle size, pressure, temperature, oxygen concentration and ignition energy, but the study of multiple factor-influence was rare and primary. In this paper we will apply the principal component analysis to reveal the main parameters affecting the coal quality index and the MEP.

Experimental design

In this experiment, fourteen types of coals are selected for the test after being crushed and screened (standard 200 sieve mesh). The proximate analysis of the fourteen types of coal is shown in tab. 1. Li *et al.* [8] measured the explosion pressure of coal dust under different concentrations with a standard 20 L stainless steel spherical vessel, and pointed out that 250 g/m^3 is the most dangerous concentration. Therefore, in this article, the concentration of coal dust used for the experiment is selected as 250 g/m^3.

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Table 1. Proximate 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

M_{ad} – moisture on air dry basis, A_{ad} – ash on air dry basis, V_{ad} – volatile on air dry basis, F_{cad} – carbon content on air dry basis, A_d – ash on dry basis, V_d – volatile on dry basis, V_{daf} – volatile on dry ash-free basis, F_{cd} – carbon content on dry basis

The 20 L spherical explosion test system consists of the device body, control system, and data acquisition system. The structure is shown in fig. 1. The device body is mainly composed of a double-layer stainless steel ball with a water-cooling jacket, a dust tank, and a gas distribution system, which is a crucial part of the test system. First, the volume of the dust tank was 0.6 L, and the dust tank was pre-aerated to 2 MPa before experiment. Then, coal dust was injected into the ball by the dispensing nozzle in the high pressure air to form a high-

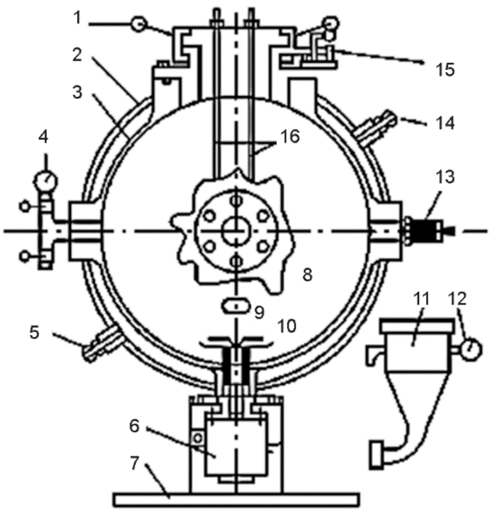

Figure 1. The 20 L spherical vessels for explosion test; *1 – sealed cap, 2 – outer jacket, 3 – inner jacket, 4 – vacuum meter, 5 – circulation water inlet, 6 – mechanical two-way valve, 7 – pedestal, 8 – sightglass, 9 – vacuum orifice, 10 – scattered valve, 11 – dust container, 12 – electro connecting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

ly turbulent coal dust cloud. The chemical ignition heads of igniter in the explosion experiment were, respectively, 1, 2, 5, 8, and 10 kJ. The chemical ignition device used in the test was made of zirconium powder, barium nitrate, and barium peroxide with a mass ratio of 4:3:3.

Results and analysis

The MEP of the fourteen different coal samples at the concentration of 250 g/m^3 was obtained by experiments and the results were shown in tab. 2.

Table 2. The MEP of fourteen different coal dusts

Coal sample number	1#	2#	3#	4#	5#	6#	7#
MEP [MPa]	0.5947	0.5565	0.6199	0.6407	0.4066	0.5368	0.6121
Coal sample number	8#	9#	10#	11#	12#	13#	14#
MEP [MPa]	0.5420	0.6194	0.6615	0.4712	0.5867	0.5107	0.6596

Coal dust explosion involves many complicated physical and chemical processes, and its detailed mechanism is not very clear up to now. From the point of view of particle ignition, the mechanism of coal dust explosion mainly includes gas phase ignition mechanism and surface heterogeneous ignition mechanism. Compared with combustion, the explosion process of coal dust generally contains two typical reaction processes: the precipitation and homogeneous combustion of volatile gases and heterogeneous combustion of solid carbon (generally incomplete combustion), which play a vital role in the overall reaction rate of coal dust [8-12]. As can be seen from figs. 2 and 3, the MEP of coal dust tends to increase with the increase of FC_{ad} and V_{d}. The MEP of coal dust tends to decline with the increase of M_{ad} and A_{d}, as can be seen from figs. 4 and 5. 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 fuel combustion, water evaporation takes heat, and water vapor absorbs a lot of heat, which affects the release rate of heat of fuel combustion. According to the mechanism of coal dust explosion, explosive gas separated from particle surface after being heated is involved in coal dust explosion to promote the development of explosion, while ash absorbs some heat in the process of incineration and inhibits the occurrence of explosion, which have the opposite effect.

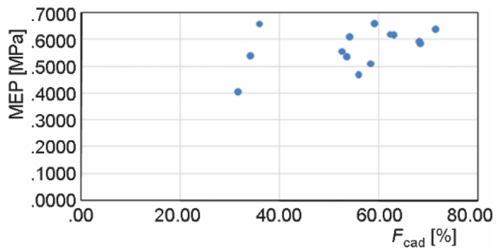

Figure 2. Evolutions of MEP with F_{cad}

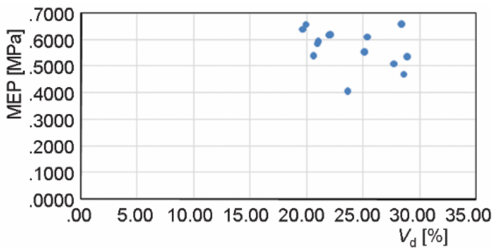

Figure 3. Evolutions of MEP with V_{d}

In order to analyze the problem comprehensively, a number of related coal quality index variables should be involved in the study of the influencing factors of the MEP of coal dust. Although these variables have influence on the MEP of coal dust, some of them are related to each other, resulting in increased computational complexity and difficulties in rational

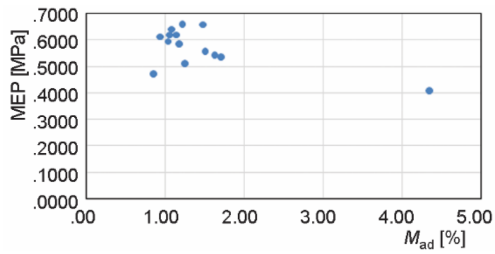

Figure 4. Evolutions of MEP with M_{ad}

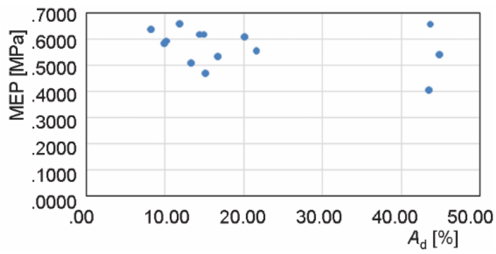

Figure 5. Evolutions of MEP with A_d

analysis. Therefore, it is necessary to *diagnose* the correlation of the original variables, use the correlation to *transform* these variables, use less new variables to reflect most of the information provided by the original variables, and then analyze the new variables to achieve the goal of solving the problem. The eight coal quality indexes selected in this paper 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). According to the data provided in tab. 1, the observation matrix, X of eight coal quality indexes of the fourteen coal samples was obtained. The X is a 14 × 8 matrix whose 8 columns represent 8 coal quality indexes and 14 rows represent 14 different coal samples. The k^{th} column of X is denoted as X_k $(k = 1, 2, \cdots, 8)$. The MEP of the 14 kinds of coal powder is Y. The correlation coefficients were shown in tab. 3.

Table 3. Table of correlation coefficient

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	Y
X_1	1.000	.607	–.075	–.656	.625	–.014	.645	–.643	–.638
X_2	.607	1.000	–.295	–.964	1.000	–.260	.776	–.965	–.301
X_3	–.075	–.295	1.000	.034	–.293	.998	.358	.035	–.332
X_4	–.656	–.964	.034	1.000	–.965	–.004	–.915	1.000	.433
X_5	.625	1.000	–.293	–.965	1.000	–.257	.779	–.966	–.314
X_6	–.014	–.260	.998	–.004	–.257	1.000	.398	–.003	–.371
X_7	.645	.776	.358	–.915	.779	.398	1.000	–.914	–.587
X_8	–.643	–.965	.035	1.000	–.966	–.003	–.914	1.000	.425
Y	–.638	–.301	–.332	.433	–.314	–.371	–.587	.425	1.000

According to tab. 3, the autocorrelation of coal quality indexes is analyzed, and some autocorrelation coefficients even reach 1.000, which indicates that the eight coal quality indexes have a serious autocorrelation. This will make the information provided by coal quality index data overlap to some extent. Therefore, the principal component analysis method is adopted to eliminate the autocorrelation and reduce the data dimension. All of the correlation coefficient between Y and $X_1, \cdots, X_8$ is more than 0.3, and the maximum is –0.638, indicating that there is a certain correlation between them, which is applicable to the analysis of the influence of coal quality index on the MEP. Principal component analysis can be used to solve the serious correlation between independent variables in regression analysis. The covariance matrix, S, of the sample data can be obtained from the observation matrix X, and:

$$S = \begin{bmatrix} 0.758 & 6.782 & -0.222 & -7.318 & 7.183 & -0.042 & 3.355 & -7.141 \\ 6.782 & 164.556 & -12.876 & -158.462 & 169.424 & -11.464 & 59.442 & -157.959 \\ -0.222 & -12.876 & 11.594 & 1.504 & -13.191 & 11.690 & 7.292 & 1.501 \\ -7.318 & -158.462 & 1.504 & 164.276 & -163.415 & -0.184 & -70.088 & 163.599 \\ 7.183 & 169.424 & -13.191 & -163.415 & 174.522 & -11.688 & 61.518 & -162.834 \\ -0.042 & -11.464 & 11.690 & -0.184 & -11.688 & 11.832 & 8.171 & -0.143 \\ 3.355 & 59.442 & 7.292 & -70.088 & 61.518 & 8.171 & 35.699 & -69.689 \\ -7.141 & -157.959 & 1.501 & 163.599 & -162.834 & -0.143 & -69.689 & 162.977 \end{bmatrix}$$

The principal diagonal elements of *S* are quite different. If the sample data principal component is extracted from *S*, the information extracted from the principal component will be concentrated in variables with large variance, resulting in information omission and result distortion. Therefore, we start from the covariance matrix of standardized sample data, that is, from the sample correlation matrix, *R*, to extract the principal components. The *R* can be obtained by the observation matrix, *X*, and:

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

The correlation matrix, *R*, described the close degree of the linear correlation between the variables, which was used to extract the principal components of 8 coal quality indexes which affecting the MEP of the coal dust. The results are shown in tab. 4.

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

As can be seen from tab. 4, the eigenvalue of the first principal component is 5.193, which explains 64.918% of all information, while the eigenvalue of the second principal component is 2.278, which explains 28.472% of all information. The cumulative contribution rate of the first two principal components reached 93.39%, indicating that the first two principal components can reflect the information of 93.39% (> 85%) provided by the original eight coal quality indexes. Therefore, the extraction of the first two principal components was determined. The coefficients of the standardized variables in the principal components of the first two standardized samples (that is, the orthogonal unitized eigenvector e_1^*, e_2^* corresponding to the two eigenvalues) 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^*
e_1^*	0.0618	0.0819	–0.0088	–0.0838	0.0822	–0.0051	0.0752	–0.0837
e_2^*	0.0091	–0.0586	0.2890	–0.0187	–0.0578	0.2903	0.1317	–0.0184

The first two standardized sample principal components can be obtained from tab. 5:

$$F_1 = 0.0618x_1^* + 0.0819x_2^* - 0.0088x_3^* - 0.0838x_4^* + 0.0822x_5^* - \\ -0.0051x_6^* + 0.0752x_7^* - 0.0837x_8^* \quad (1)$$

$$F_2 = 0.0918x_1^* + 0.0586x_2^* - 0.289x_3^* - 0.0187x_4^* + 0.0578x_5^* - \\ -0.2903x_6^* + 0.1317x_7^* - 0.0184x_8^* \quad (2)$$

It can be seen from eqs. (1) and (2) that fixed carbon content, ash content and volatile component are the main factors affecting the MEP of coal dust. In order to eliminate the co-linearity of the standardized variables, three regression models are used in this paper by principal component regression. For Model 2, the significance index Sig = 0.011 < 0.05, the correlation index R = 0.747, and the data error is small, which can be used as the prediction model of MEP of coal dust. The regression equation:

$$Y = 0.61 - 0.078F_2 - 0.208F_1^2 \quad (3)$$

given by Model 2 was selected for data fitting, and the predicted value of the MEP of 1#-14 # coal dust and its error with the experimental value were calculated, as shown in tab. 6.

Table 6. The predicted value of the MEP of 1# – 14# coal dusts and its error

Coal sample number	1#	2#	3#	4#	5#	6#	7#
Calculated value [MPa]	0.6198	0.5727	0.6163	0.6434	0.4164	0.5492	0.5701
Error	0.0251	0.0162	0.0036	0.0027	0.0098	0.0124	0.0420
Coal sample number	8#	9#	10#	11#	12#	13#	14#
Calculated value [MPa]	0.5572	0.6168	0.5435	0.5473	0.6221	0.5476	0.5962
Error	0.0152	0.0026	0.1180	0.0761	0.0354	0.0369	0.0635

In order to verify the reliability of the model, another five kinds of coal dust are selected in this paper. The proximate analysis, the MEP and the predicted value of the MEP calculated by Model 2 of these coal dusts are shown in tab. 7. It can be seen from tabs. 6 and 7 that the experimental value of the MEP of coal dust is basically consistent with the predicted value, and the error is within the acceptable range, indicating that the prediction of the MEP of coal dust explosion by Model 2 is reliable.

Conclusion

In this paper, the MEP of coal dust with different coal quality indexes is studied by using a Siwek 20 L spherical explosion test system, the effects of volatile component, mois-

Table 7. Proximate analysis, MEP 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} [%]	MEP [MPa]	Predicted value [MPa]
15#	8.36	12.71	37.31	41.62	13.87	40.71	47.27	45.42	0.5578	0.5597
16#	2.68	3.94	40.98	52.4	4.05	42.11	43.89	53.84	0.5485	0.5475
17#	1.31	65.27	18.71	14.71	66.14	18.96	55.98	14.90	0.5903	0.5808
18#	1.08	8.07	19.40	71.45	8.16	19.61	21.35	72.23	0.6295	0.6320
19#	4.05	12.07	30.33	53.55	12.58	31.61	36.16	55.81	0.6014	0.6040

ture content, fixed carbon content and ash content on the MEP are analyzed. The MEP of coal dust tends to increase with the increase of volatile component and fixed carbon content and decrease with the increase of ash and moisture content. Based on the principal component analysis of multivariate statistical analysis, the main factors affecting the MEP of coal dust were obtained by extracting the principal component from the coal quality indexes. Through comparative analysis, a regression model is obtained to predict the MEP of coal dust with different coal quality components. It can be seen that the model is reliable.

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