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ABSTRACT: The coal and gas outburst accident on May 20, 2007 at Sihe Coal Mine is unique in that there is no or very little soft coal in the coal seam and that the coefficient of coal strength is very high. It was also indicated in the outburst that there is a very high gas content of 20-30 m^3/t in the coal seam nearby the outburst site. Based on field test and observations, together with laboratory experiments, detailed analysis was conducted on controlling factors of coal and gas outburst potential at Sihe Coal Mine. Stress data available from Sihe Coal Mine, northern China and other parts of world, were also taken into account to facilitate the analysis. The results show that the stress level is not abnormal compared to other coal fields in China prone to outbursts, and that the gas contained in the coal seam is the main factor that triggered the outburst. The results show that outbursts are limited to only a small part of the whole coal seam and that the East part of coal field is not prone to outbursts.

INTRODUCTION

Sihe Coal Mine, owned by Jincheng Anthracite Mining Group, is located in Jincheng City. It currently has the capability to produce annually 10.8 Mt of coal. There are three coal seams and all were formed in Permian. One of them, namely the number 3 coal seam, is the only one believed to be outburst prone, and its thickness varies in the range of 4.45 to 8.75 m, with an average of 6.31 m. The coal seam strikes NNE and dips to the NWW at an angle of 2 to 10°. Geological structures are simple, and the coal seam has not been tectonically disturbed. Underground observations indicate that the seam keeps its original sedimentary structure. On average, the coal seam has an overburden thickness of 300 to 600 m.

Geologically, Sihe Coal Mine is located at the southeast end of the composite syncline of Qinshui Basin, North China. Geologic structure in the area consists of faults, joints, and igneous dykes. The most significant geologic structure is the north-east oriented Panhe Syncline that divides the Sihe coal field into Main West and Main East. The mine was connected underground before the outburst on May 20, 2007, and it has been isolated as two independent parts by permanent shields approximately along the Syncline. Generally speaking, geological structures in Main West are more complicated than that in Main East, which contributes to the potential of outburst occurrence in Main West area.

OUTBURST AT SIHE COALMINE

On May 20, 2007, an outburst occurred at Sihe Mine, Jinchang Mining Group, and four coal mine workers were buried in the ejected coal and killed. Approximately 370 t of coal were blowout with the release of about 87 000 m^3 of gas in the outburst.

Mining and development of entries

Because of the outbursts in neighbour privately owned coal mines, the mine is prudent in dealing with outburst potential. Typically, "four-in-one" measures are employed to prevent and control outbursts in entry development whenever there is obvious evidence of outburst potential, including gas surge emission from boreholes, dramatic change of coal seam, high level of gas content in ventilation air etc. Coal Mine Safety Regulations provide that the "four-in-one" measure be taken with high alert to prevent outburst occurrence, which consists of four steps. The first step is the assessment of outburst potential by K_1 index at cross cut No 6, which is an indicator of gas emission velocity from coal drilling yields. The critical value is 0.5, and if it is higher than 0.5, the heading face of the entry is believed to be outburst prone and then over 20 boreholes of 89 mm in diameter are drilled into the heading face to destress and release gas in coal seam. When all boreholes are completed, K_1 index is again tested to make sure it is

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less than 0.5 and the danger of outburst has been eliminated. Then normal operations on the heading face are executed with rescue chamber and rescue ventilation system set up nearby.

Outburst on May 20

The #6 cross cut was driven seven days per week during three 8-hour shifts. On May 9, 2007, the morning shift crew tested both K_1 and S (borehole drilling yields), and the maximum K_1 and S were 1.77 ml/(g·min$^{1/2}$) and 2.5 kg/m respectively, which indicated an impending outburst potential. Then the development operations were stopped and measures against outbursts were executed to eliminate the potential. According to regulations of Sihe, tests on K_1 and S were carried out on May 18, and they were 0.49 ml/(g·min$^{1/2}$) and 3.2 kg/m respectively, surely suitable for resuming development operations. Before mid shift on May 20, 6m were driven, with 2m left allowed to be finished by mid shift. At about 13:22, May 20, an outburst occurred, with the ejection of 370 t of coal and the release of 87 000 m^3 of gas, mainly methane. Four coal mine workers were killed in the outburst and several others were injured.

Figure 1 - Normal coal from Sihe outburst site (left) and tectonically disturbed coal from outburst cavity at Menin Mine, Henan, China (right)

The site of the outburst was at the heading face of #6 cross cut, which was planned to connect two main airways in Main West. The outburst is characterized by its no connection with tectonically disturbed or soft coal and by its release of huge volume of gas. Worldwide experiences (Shepherd, *et al.*, 1981; Frodsham and Gayer, 1999; Liu, *et al.*, 2008) have shown that almost all outbursts are accompanied by tectonically disturbed coal or soft coal. Usually, the soft coal is formed by crushing coal seams into coal fines by thrusting, folding or sliding in coal seams millions of years ago.

After the accident, the authors made an underground visit to the outburst site and made some observations. Onsite observation (Liu, *et al.,* 2008) showed that coal seam close to the outburst site is normal without soft coal, and sedimentary bands can be clearly seen as is indicated by the left side photo shown in Figure 1.

UNDERGROUND AND LABORATORY TESTS

After the accident, the authors conducted underground onsite observations on tectonically disturbed coal, underground tests on indexes for assessment of outburst potential and laboratory test, with aims to analyse the causes of the outburst and to assess outburst potential in the Main West and Main East.

Distribution of tectonically disturbed coal

Tectonically disturbed coal or soft coal is coal whose original sedimentary structure is totally damaged by geological movements, with very low strength and high gas emission rate. Traditionally, it is a primary condition for a coal seam to be outburst prone when the overburden is less than 600 m. Therefore, it is of critical value to have a clear picture of its distribution if an accurate assessment of outburst potential is to be made. Two methods are employed to obtain the distribution of soft coal: one is direct underground observations; another is to calculate by borehole logging data.
The results obtained from both methods show that soft coal layers are not well developed and their total thickness is generally under 0.5 m, the majority of which, approximately 76%, are under 0.3 m. According

to our research at Huainan coal field, Anhui Province and Hebi coal field, Henan Province, at least 0.90 m of soft is necessary for a coal seam to be prone to outburst occurrence. It is worth noting that there is no soft coal in the vicinity of the outburst on May 20.

Laboratory test on gas desorption from coal

An experimental system (see Figure 2) was set up to test gas emission rules and outburst potential assessment indexes K_1 and $\Delta h2$, of which K_1 was used to assess outburst danger before the May 20 accident. The system has the capacity to test sample of 2.5 kg of coal, allowing more accurate test results than that carried out underground with only 10 g of coal

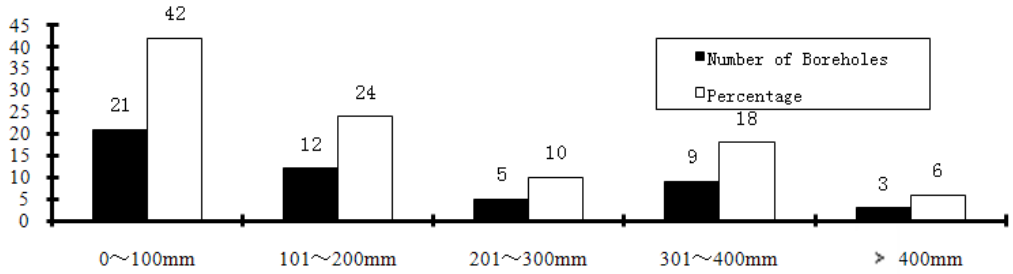

Figure 2 - Distribution of soft coal calculated by borehole logging data

Tests were conducted on coal samples from the ejected coal of the outburst. Coal samples from other coal fields such as Jiaozuo and Yima were also tested for comparison. Test method was described by Wen in details (Wen, 2008). The results show that there exists a linear relationship between gas pressure and index K_1. Although coal samples are different, their trends for the relations between index K_1 and gas pressure are approximately the same; and the only differences are their intersections with K_1 axis.

For hard coals with less volatile gas contents and higher strengths such as Jincheng and Zhaogu, their respective values of index K_1 are much lower than those from coals with higher volatile contents and less strengths such as Yima and Jiulishan. It can be estimated that for coal from Jincheng, when K_1 is higher than 0.5 ml/(g·min$^{1/2}$) the gas pressure can be as high as 1.5 MPa, and if K_1 reaches 1.77 ml/(g·min$^{1/2}$), as is the case of the outburst accident, the gas pressure will be as high as 6.9 MPa.

In addition, the same tests were conducted for two coal samples from the Main East to further analyze gas desorption law at Sihe coal mine. It is clearly seen from both Figure 3 and Figure 4 that whatever equilibrium pressure is, gas initial desorption velocity of the soft coal is faster than that of the hard coal with little difference in gas desorption quantity.

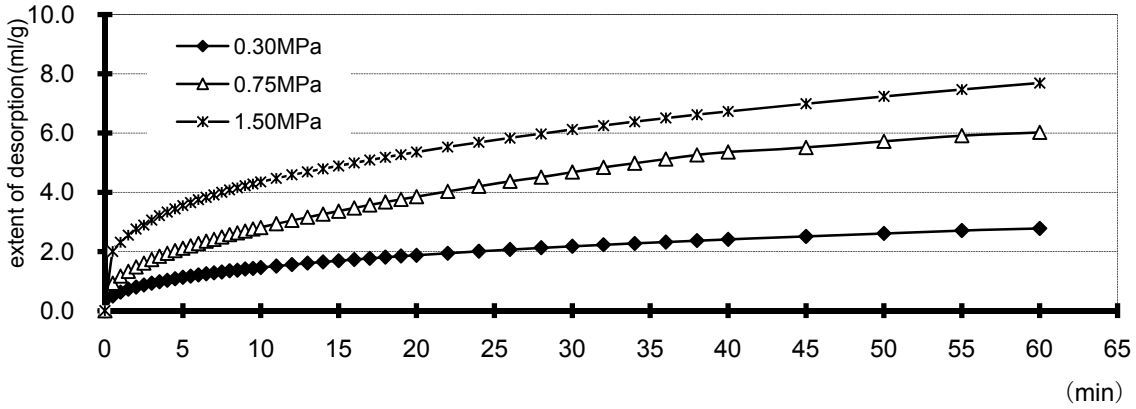

Figure 3 - Desorption law at Sihe coal mine within 60 minutes (f=1.7)

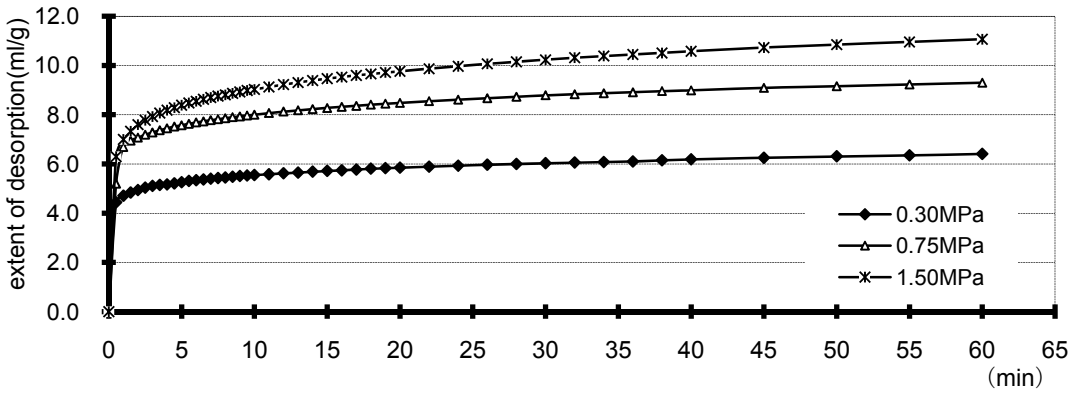

Figure 4 - Desorption law at Sihe coal mine within 60 minutes (f=0.73)

Indexes of coal properties

Because the majority of the coal seam is hard coal, two important indexes of coal properties are tested for hard coal samples at Sihe Coal Mine that keeps its original sedimentary structure perfectly. These indexes are strength coefficient *f* and Gas Emission Index (ΔP). The test results show that values of strength coefficient *f* are 1.5, which is much higher than the critical value shown in Table 3 in section 4 of this paper; and the Gas Emission Index (ΔP) ranges from 20 to 44.

ANALYSIS AND DISCUSSION

Since geological structures in Sihe are generally simple when compared to other coal mining fields, the three most important factors, namely stress level, gas content (pressure) and coal properties, will be considered to analyse and discuss the outburst.

Overburden and stress levels

The maximum overburden in the cross cut is 458 m, which is not uncommon in outburst coal mines in most parts of China. Many experts have the opinion that the outburst may have been caused by very high horizontal tress levels developed in ancient geological periods. Stress levels in Main West and Main East have been measured jointly by Coal Research Institute (2004), Beijing and Sihe Coal mine and are listed in Table 1.

Table 1 - Stress measurements in Sihe Coal Mine

Area	Overburden (m)	σ_v (MPa)	σ_{Hmax} (MPa)	Direction of σ_{Hmax}	σ_{Hmin} (MPa)	σ_{Hmax}/σ_v
Main East	303.0	8.03	16.585	N83.4ºW	8.53	2.07
	384.0	10.17	18.264	N69.2ºW	8.67	1.80
	376.0	9.96	18.928	N71.2ºW	9.76	1.90
Main West	439.7	11.65	13.00	N17.4ºW	6.74	1.12
	399.2	10.58	13.20	N63.8ºW	6.98	1.25
	410.5	10.88	13.81	N39.0ºW	7.92	1.27
	459.6	12.18	10.89	N62.7ºE	5.61	0.89
	414.6	10.99	10.80	N65.7ºE	5.92	0.98
	409.4	10.85	12.43	N79.2ºE	6.62	1.15
	410.2	10.87	13.67	N63.5ºW	7.05	1.26
	310.0	8.22	11.34	N49.7ºE	6.40	1.38
	292.4	7.75	11.74	N54.2ºE	6.70	1.51
	285.5	7.54	10.90	N43.5ºE	5.71	1.45

The data in Table 1 show clearly that stress levels in Main West and Main East are pretty normal when compared with worldwide stress levels (Brown and Hoek, 1978) and that within China (Cai, *et al.*, 2002;

Zhao, *et al.*, 2007). According to Cai *et al.* (2002), they are in the medium category and maybe lower than those in some coal fields such as Shenhuo Mining Group, east Henan Province, China, where the stress level is higher than 25.0 MPa with same overburden and there is no outburst occurrence.

The data in the table indicate that stress level in Main West is higher than that in Main East, which may not explain why the outburst occurred in Main West. However, this situation and the comparison thus made show obviously that stress level is not the dominating factor that caused the outburst on May 20.

Gas pressure and gas content

It is well established that coal seam gas pressure or gas content is one of the most important factors controlling the occurrence of outbursts. As is shown in Table 3, it is provided by Detailed Regulations of Outburst Coal Mine that coal seam with gas pressure higher than 0.74 MPa should be considered as outburst prone if the coal seam is tectonically disturbed. Thresholds of gas contents for outbursts to occur depend mainly on the geological conditions and the nature of coal seams. These gas content thresholds for the coal seams in Huainan, Anhui Province, Hebi and Zhengzhou, Henan Province are 9.0 m^3/t, 12.0 m^3/t and 8.0 m^3/t, respectively. And in Australia, the threshold is 9.0 m^3/t when the gas involved is methane (Liu, *et al.*, 2008).

Data from coal field prospecting period show that coal seam pressures range from 0.8 to 2.12 MPa and gas contents from 10.70 to 26.80 m^3/t. Borehole gas content closest to the outburst site is 16.60 m^3/t, which is probably 20-50% less than its true value according to China's empirical data obtained from prospecting borehole drilling. Although immediate onsite data of gas contents or gas pressures are not available to evaluate exactly how the outburst was influenced by gas storage status, however, the gas pressure may be as high as 6.90 MPa, as was indicated by our previous laboratory test and estimation. Chongqing Coal Research Institute (2005) has tested some adsorption parameters of gas on coal samples from Main West, and the results show an average *Langmuir* parameter a=40 m^3/t, b=1.6 MPa^{-1}. Based on the previously estimated pressure and adsorption parameters of gas on coal at Sihe, it is estimated the gas contents are higher than 36.68 m^3/t.

Table 2 - Some available parameters of the most important outbursts in 2007

Date	Coal Mine	Coal Ejected (t)	Gas Released (m^3)	Gas Released Per Ton of Coal (m^3/t)
04-19	Dashucun Mine,	1270	93 000	73.20
04-18	Taoer Mine, Hebei	475	65 000	136.8
05-20	Sihe, Shanxi	370	87 000	235.13
06-07	Jinjia Mine, Guizhou	204	8 000	39.80
11-08	Qunli Mine	402	37 283	92.74
11-12	No.10, Henan	2000	40 000	20.00

The unusually high gas content and gas pressure can be established by the large volume of gas released by the May 20 outburst. Table 2 is a list of six most important outbursts that occurred in 2007 in China, which indicates that gas release from the Sihe outburst is the highest, with 235.13 m^3 of gas per ton of coal. From Table 2 and other outburst experiences from China and other countries, for the majority of outbursts, the average gas release per ton of coal is in the range of 30 to 150 m^3. The high volume of gas release from the outburst on May 20 indicates high gas content and high gas pressure in coal seam. Nevertheless, the outburst occurred after gas drainage of almost 10 days. If it had occurred without the gas drainage, much more gas release could be expected because of its unusually high gas content and gas pressure.

Coal properties

Various works **(**Frodsham and Gayer, 1999; Liu *et al.*, 2008; Wen, 2008**)** found that the nature of coal seams plays important role in outburst occurrence. In China, coal is classified into 4 categories (Liu *et al.*, 2008), of which category I and II are considered as not outburst prone, category III and IV are tectonically disturbed soft coal and are considered outburst prone. Based on approximately 1000 laboratory tests and observations on coal samples from more than 10 coal fields in Guizhou, Anhui and Henan, for about 95%

of disturbed coal samples, their values of *f* and ΔP are above their corresponding thresholds, that is *f* less than 0.5 and ΔP more than 10 (Table 3).

Table 3 - Thresholds of outburst potential parameters in coal seams

Coal Strength Coefficient of (*f*)	Gas Emission Index (ΔP)	Gas Pressure (MPa)	Coal Structure
<0.5	>10	>0.74	Tectonically disturbed

From the laboratory test results, coal samples from site of the outburst on May 20 are not outburst prone because they are not tectonically disturbed and their strength coefficient are much higher than 0.5.

Cause of outburst on May 20

As is shown in Table 3, it is provided by Detailed Regulations of Outburst Coal Mine that coal seams with gas pressure higher than 0.74 MPa should be considered as outburst prone if the coal seam is tectonically disturbed. For coal seam in Main West at Sihe Coal Mine, its stress level is normal, its overburden is 458 m, and it was not tectonically disturbed. Compared to other normal coal seams, which are not outburst potential at all, the only and obvious difference is that the coal seam at Sihe Coal Mine has unusually high gas pressure and high gas content.

It is, therefore, concluded that the main cause of the outburst at Sihe Coal Mine is the large volume of gas stored in coal seam. This conclusion is the basis for the future assessment of outburst potential at Sihe Coal Mine.

ASSESSMENT OF OUTBURST POTENTIAL

Based on the analysis and discussion made previously on factors that may affect outburst potential at Sihe Coal Mine, it is surely possible to assess outburst potential by utilizing data of soft coal distribution in coal seam and data of gas contents.

Standards for outburst potential assessment

Compared to coal fields that are liable to outbursts, the #3 coal seam is unique in that it demonstrates very thin layers of tectonically disturbed coal or none at all and that it has unusually high gas pressures or gas contents. Currently, we are not sure exactly what is the lowest gas pressure or content for the coal seam to be safe from outburst occurrence. It is, however, certain that when gas content is lower than 12 m^3/t, the coal seam will not be outburst prone at all.

Table 4 - Gas contents in Main East

Measurement Sites	Gas Content (m^3/t)	Components(%)	
		N_2	CH_4
Outby 38 m, 3# Cross Cut, 23053 Entry	9.25	4.95	95.05
Left, Outby 6 m, 5# Cross Cut, Belt Entry	6.35	7.88	92.12
Right, Outby 6 m, 5# Cross Cut, Belt Entry	4.22	27.40	72.60
Entry 43013	9.74	7.64	92.36
Entry 41014	8.08	0.97	99.03
Inby 42 m, #1 Cross Cut, Entry 41013	10.97	7.31	92.69
Outby 27 m, #3 Cross Cut, Entry 43013	7.82	7.64	92.36
Outby 16 m, #5 Cross Cut, Entry 43014	3.27	48.9	51.10
Outby 45 m, #5 Cross Cut, Entry 43012	6.38	10.40	89.60
Outby 30 m, 15 Cross Cut, Entry 43013	7.44	8.89	91.11

The safe gas content level of 12 m^3/t can be established by Table 4. Table 4 is valid for low gas contents and overburden less than 600 m. For coal from Sihe, If the gas pressure is 0.74 MPa, the corresponding gas content is approximately 21.68 m^3/t, as is calculated by *Langmuir*'s formula with parameters a=40.0

m^3/t and b=1.6 MPa^{-1}. Based on the principle that predictive indexes of coal seam outburst upgrading should guarantee clear and safe alert of outbursts, when gas content is lower than 12 m^3/t, the coal seam will not be outburst prone at all, when gas content falls in the range of 12 to 20m^3/t, the coal seam should be managed as outburst threaten area and when gas content higher than 20 m^3/t, the coal seam will be determined as outburst potential.

Outburst potential assessment

Coal seam gas contents in the Main East obtained from prospecting period range from 6.88 to 11.28 m^3/t, and gas pressure from 0.1 to 0.29 MPa. Table 4 provides the gas contents measured underground, and the highest gas content is 10.97 m^3/t. There, the Main East is not prone to outbursts.

In the Main West, 19 gas pressures were measured by Chongqing Coal Research Institute (2005). The maximum gas pressure is 2.12 MPa, and the average gas pressure is 1.33 MPa. The gas contents obtained during coal field prospecting period are in the range of 10.7 to 26.80 m^3/t. According to the standards set up previously, as a whole, outbursts are limited to only a small area of the coal seam.

CONCLUSIONS AND SUGGESTIONS

The principal conclusions drawn from this study are as follows:

- The outburst on May 20, 2007, in Main West at Sihe Coal Mine was caused mainly by unusually large volume of gas stored in the coal seam;
- A gas content of 12 m^3/t has been established as the reliable and secure standard for assessment of coal seam outburst potential in Sihe Coal Mine;
- Main East at Sihe is not outburst prone; and to the contrary, Main West is evaluated as potential to outbursts;
- Collaborative research among universities and research institutes is necessary to determine and clarify the exact conditions of outburst occurrence in coal seams similar to Sihe Coal Mine.

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