APPLICATION OF STATISTICAL PROCESS CONTROL THEORY IN COAL AND GAS OUTBURST PREVENTION

Shaojie Hou
Computer Center, Hebei University of Economics and Business, Shijiazhuang, China
Post-doctoral Scientific Research Workstation, Shanxi Coking Coal Group CO., LTD, Taiyuan, China
Yuwei Zhang
Computer Center, Hebei University of Economics and Business, Shijiazhuang, hina
Shijiazhuang Vocational College of Finance Economics, Shijiazhuang, China
Yuanping Cheng
Key Laboratory of Gas and Fire Control for Coal Mine,China University of Mining & Technology, Xuzhou, China

Abstract

With Chinese coal exploitation extending to depth rapidly, a large number of coal and gas outburst accidents happened and resulted in thousands of casualties in the last decade. Coal and gas outburst prevention project has become the prerequisite of underground coal mining, but its process control ability is especially poor. By integrating statistical process control theory into the process of coal and gas outburst prevention, three urgent problems were solved. First at all, data structure of the process inspection parameters was designed asvectors, which only consisted of principle elements and formed data series as time went by. Secondly, based on sample data of the experimental area, statistical characteristic of inspection parameters was gained and their X-R_s control charts were drawn. Finally, performance of process running statuses that might be in control or beyond control were analyzed in detail. When the process was in control, curves should slightly fluctuate around their center lines and between upper control limits and lower control limits. Otherwise, the process was beyond control, in which X control charts were used to identify anomalies of data value fluctuation and R_s control charts were used to identify anomalies of data fluctuation amplitudes. By the experimental application in Hexi colliery of China, the interdisciplinary research was proved to be helpful to improve process control ability and then prevent coal and gas outburst accidents.

Keywords: Coal and gas outburst, statistical process control, control chart, anomaly identification, coal mining

Introduction

With the rapid growth of Chinese economy, coal demand has been increasing sharply. In last ten years, coal output has soared up to 3.7 billion tons in 2013 from 1.8 billion tons in 2004. Meanwhile, coal exploitation depth of almost all Chinese underground collieries has exceeded 800m (Liu *et al*, 2010). The phenomenon of three high and two low, namely high geo-stresses, high gas, high inhomogeneous, low permeability and low coal mass strength, became more and more serious, which gave rise to a large number of coal and gas outburst accidents (Hou *et al*, 2013). Official accident statistical reports issued by China State Administration of Coal Mine Safety manifested annual casualties directly caused by coal and gas outburst accidents were continuously over 300 in last five years.

Funded by Chinese government, intensive research and practice has been done to prevent coal and gas outburst hazard in the last decade, and two relatively mature technical systems have been widely recognized up to now. One is protective-layer mining and relief-pressure gas drainage technique, which could eliminate the gas content of protected coal layer. Another is regional strengthening gas drainage technique that could eliminate the gas content of single outburst coal layer (Cheng *et al*, 2009).

However, the process of regional coal and gas outburst prevention is so different from industrial processes of other fields that it is difficult to be controlled comprehensively for the following reasons:

1) Duration of regional coal gas outburst prevention process is often more than 1 year and even 2-3 years. In the period, many things such as personal redeploy, project adjustment, data storage might happen and then disorganize the original management.

2) Two typical technical systems contain multifarious measures with poor automation and digitalization. Mainly all operations, including designing, constructing, validating, etc. have to be implemented manually.

3) Along with the process, massive data were recorded as Word documents, Excel dataset, CAD drawings, etc. Various data storage forms made standardization and digitalization work impossible.

Amount of accidents analysis reports of coal and gas outburst illustrated that lacking the process control ability was the chief culprit (SAWS, 2009). Scholars presented a large number of achievements in last years for this. J.H. Fu (2005) proposed card filling method to record gas parameters detected periodically. R. Balusu *et al* (2007) tracked laws of gas drainage data of many Australia underground collieries by sequence chart. L.J. Ma (2009), J.T. Guo (2009), I.B. Shirokov *et al* (2010) studied the law of gas emission and early warning method of break bound. P.W. Shi *et al* (2002) proposed close-loop anomaly recognition method, consisted of five primary links, namely forecast, analysis, monitoring, recognition and control, which were tested successfully in some collieries of Zhengzhou Coal Industry Co. Ltd., China. D.D. Song (2007), Ms. Warsha, *et al* (2011) proposed a working-face-based method to track the emission parameters of coal gas, in which the whole coal mining face rather than detecting points were regarded as the study object.

In conclusion, various and massive methods were put forward and tested in last years. But their chaotic theoretical basis made them non-standardized, incomplete and disordered. Based on statistical process control (SPC) theory that has been successfully applied in many fields such as petrochemical engineering, machinery manufacturing, etc., this paper will present a more rational and normalized method to track coal and gas outburst prevention process and predict anomalies. Because of the especially close relations among this process, coal and gas outburst accidents and miner lives, the study has important practical significance.

Statistical Process Control Theory

As the most widely used quality management technology, SPC integrated the applied statistics into process industry and achieved great success. According to SPC theory, running status of any industrial process can be reflected by its inspection parameters, which fluctuate affected by random factors and system factors, as shown in Fig.1. [22]

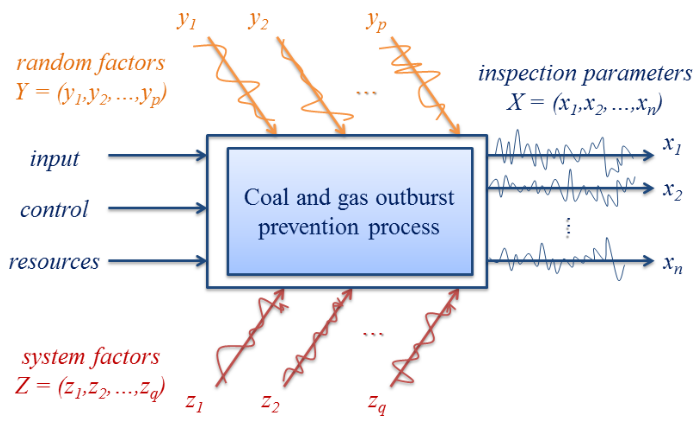


Fig.1 Schematic diagram of inspection parameters fluctuation

In Fig.1, the relationship among three vectors *X*, *Y* and *Z* can be described as the following function:

$$X = f(Y, Z) \tag{1}$$

where *X* is inspection parameters; *Y* is random factors; and *Z* is system factors.

It has been proved that *{X}* sequence would fluctuate stably and randomly when the industrial process only affected by *{Y}* sequence. Otherwise anomalies emerged.

Making the sequence number of *{X}* as horizon axis coordinates, and making its values as vertical axis coordinates, the curve of inspection parameters could be drawn. Based on the 3σ principle, Central Line (CL), Upper Control Limit (UCL) and Lower Control Limit (LCL) could be drawn (Montgomery, 2008). This chart, named as process control chart, could objectively reflect four common running statuses of the industrial process, including controlled, break bound anomaly (named as type 1 anomaly), chain anomaly (named as type 2 anomaly) and trend anomaly (name as type 3 anomaly), as shown in Fig.2.

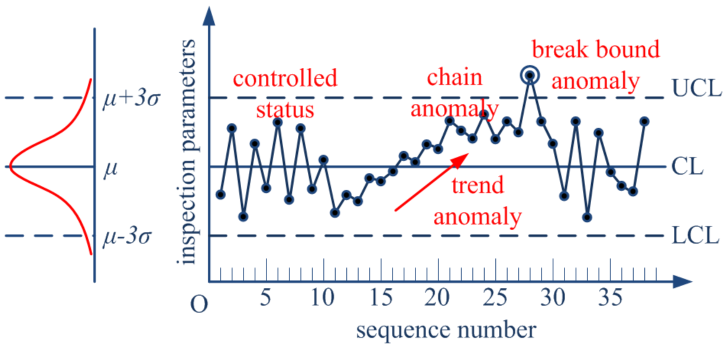


Fig.2 Schematic diagram of process control chart

Inspection Data Series

Although multifarious measures of regional coal and gas outburst prevention process are different in detail, they have the same data structure as time goes by, which can be classified into two types, namely construction parameters and gas elimination parameters. The former is composed of the designing and constructing records of roadway, working face, borehole field, boreholes and spatial relations among them. The latter is to keep track of the gas elimination quantity, including gas drainage quantity of sealed pipes with negative pressure and gas windblown quantity of return-air roadways (Hou *et al*, 2013), as shown in Fig.3.

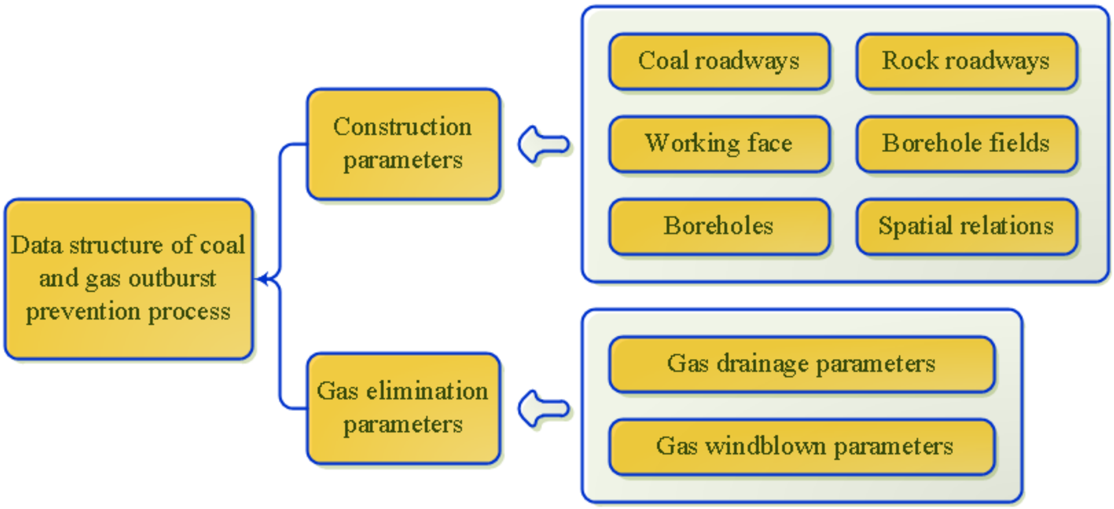


Fig.3 Data structure of regional coal gas outburst prevention process

Now construction parameters are often recorded in Excel or drawn in CAD manually, but gas elimination parameters can be directly exported from the gas monitoring system that has been installed in most Chinese collieries.

In view of construction parameters, our target is to keep consistent between designing and construction. Taking boreholes as an example, the designing parameters are defined as the following vector:

$$\vec{B} = (id, x, y, z, \alpha, \beta, l, \phi) \tag{2}$$

where $\vec{B}$ is the designing vector; *id* is the identifier of borehole; *x*, *y* and *z* are the coordinate of drilling position, /m; α is the azimuth angle of borehole, /°; β is the inclination angle of the borehole, /°; *l* is the borehole length, /m; ϕ is the cross-section diameter of the borehole, /mm.

In correspondence with (2), construction parameters can be defined as the vector:

$$\vec{B}' = (id, x', y', z', \alpha', \beta', l', \phi', t) \tag{3}$$

where $\vec{B}'$ is the construction vector; *t* is the construction time and the rest elements have the same means as its design.

To describe the construction deviation from its design, we do difference transformation between $\vec{B}$ and $\vec{B}'$, retaining element *t*, shown as the following vector:

$$\Delta\vec{B} = \vec{B}' - \vec{B} = (id, \Delta x, \Delta y, \Delta z, \Delta\alpha, \Delta\beta, \Delta l, \Delta\phi, t) \tag{4}$$

where $\Delta\vec{B}$ is the deviation vector and *t* is the construction time.

Other construction parameters of coal roadways, rock roadways, working face, borehole fields and spatial relations can be expressed as the analogous vectors. In order to simplify the description, the other vectors were omitted in this paper.

Referring dataset explored from gas monitoring system, gas elimination parameters can be described as the following vector:

$$\begin{cases} \vec{D} = (q_d, c_d, k_d, t_d) \\ \vec{W} = (s_w, q_w, c_w, m_w, t_w) \end{cases} \tag{5}$$

where $\vec{D}$ is the gas drainage vector, in which q_d records the mixed gas drainage flow, /m^3/s; c_d records the gas concentration of sealed pipes , /%; k_d records the instantaneous temperature, /degree; t_d records the testing time of gas drainage; $\vec{W}$ is the gas windblown vector, in which s_w records the cross-sectional acreage of return-air roadway, /m^2; q_w records the mixed gas windblown flow, /m^3/s; $c_w$records the gas concentration of return-air roadway, /%; m_w is the daily coal production of related working face, /ton; t_w is the testing time of gas windblown.

Therefore, $\Delta\vec{B}$, $\vec{D}$, $\vec{W}$ and those omitted vectors consist the inspection data series of coal and gas outburst prevention process.

Data Tracking and Anomaly Identification

Hexi colliery, located in Liulin city, Shanxi province of China, has been authenticated continuously as the high gas mine in last five years. According to coal and gas outburst prevention regulations (SAWS, 2009) and gas drainage provisional regulations for collieries (SAWS, 2011), rational measures must be taken.

The NO.3312 working face is selected as the experimental area of this paper because related boreholes construction and gas drainage projects are under way now and their sample data are representative. This working face is to mine the NO.3 coal seam with gas outburst danger, which average thickness is 1.75m and average inclination is 6 degrees. It has been measured that the gas content is high, 8.42m^3/t. Since Jan. 2013, hundreds of boreholes along coal seam has been constructed, sealed and connected into the global gas drainage system with negative pressure. Part of inspection data series $\{\Delta\vec{B}\}$ were given in Table.1.

Table.1 Inspection sample data of coal and gas outburst prevention process

id	*Δx/m*	*Δy/m*	*Δz/m*	*Δα/°*	*Δβ/°*	*Δl/m*	*Δϕ/mm*	*t*
63#	0.00	0.00	0.00	-0.09	-0.21	1.37	0.00	2013/5/11
64#	0.00	0.00	0.00	0.54	-0.10	0.93	0.00	2013/5/11
65#	0.00	0.00	0.00	0.85	-0.20	2.13	0.00	2013/5/12
66#	0.00	0.00	0.00	1.47	-0.85	1.84	0.00	2013/5/12
67#	0.00	0.00	0.00	1.55	-0.24	1.44	0.00	2013/5/12
68#	0.00	0.00	0.00	2.07	-0.35	0.25	0.00	2013/5/13
69#	0.00	0.00	0.00	1.15	-1.52	1.34	0.00	2013/5/15
70#	0.00	0.00	0.00	1.11	-1.73	3.06	0.00	2013/5/16
71#	0.00	0.00	0.00	0.83	-1.01	1.74	0.00	2013/5/17
72#	0.00	0.00	0.00	0.82	-1.32	3.31	0.00	2013/5/17
73#	0.00	0.00	0.00	0.69	1.58	2.97	0.00	2013/5/18
74#	0.00	0.00	0.00	0.68	0.64	0.22	0.00	2013/5/18
75#	0.00	0.00	0.00	0.62	-0.28	0.49	0.00	2013/5/19
76#	0.00	0.00	0.00	0.52	2.98	0.98	0.00	2013/5/20
77#	0.00	0.00	0.00	0.47	-1.33	1.80	0.00	2013/5/20
78#	0.00	0.00	0.00	0.33	-0.62	2.70	0.00	2013/5/20
79#	0.00	0.00	0.00	1.34	-1.32	3.82	0.00	2013/5/21
80#	0.00	0.00	0.00	-0.29	1.33	4.97	0.00	2013/5/22
81#	0.00	0.00	0.00	3.60	0.28	0.39	0.00	2013/5/23
82#	0.00	0.00	0.00	0.55	1.08	-0.34	0.00	2013/5/24
83#	0.00	0.00	0.00	-0.97	0.48	4.71	0.00	2013/5/24
84#	0.00	0.00	0.00	0.90	-0.89	-0.26	0.00	2013/5/25
85#	0.00	0.00	0.00	0.43	2.24	4.80	0.00	2013/5/25
86#	0.00	0.00	0.00	-0.81	-1.76	3.87	0.00	2013/5/26
87#	0.00	0.00	0.00	0.28	-1.00	5.29	0.00	2013/5/27
88#	0.00	0.00	0.00	1.90	2.21	2.40	0.00	2013/5/28
89#	0.00	0.00	0.00	0.82	1.33	-2.82	0.00	2013/5/28
90#	0.00	0.00	0.00	-0.41	-5.98	-3.10	0.00	2013/5/29
91#	0.00	0.00	0.00	-0.16	0.73	3.73	0.00	2013/5/30
92#	0.00	0.00	0.00	-1.42	-1.11	-0.02	0.00	2013/5/30
93#	0.00	0.00	0.00	0.08	2.45	2.82	0.00	2013/5/31
94#	0.00	0.00	0.00	-1.23	3.01	5.82	0.00	2013/6/1
95#	0.00	0.00	0.00	1.05	-0.78	2.46	0.00	2013/6/1
96#	0.00	0.00	0.00	0.47	1.68	0.88	0.00	2013/6/2
97#	0.00	0.00	0.00	-1.81	1.38	-0.64	0.00	2013/6/3

In Table.1, deviations between designing and construction are mainly manifested in three elements that are $\Delta\alpha$, $\Delta\beta$ and Δl. By *A-D* test function of Minitab software, they were proved to fit the following normal distribution:

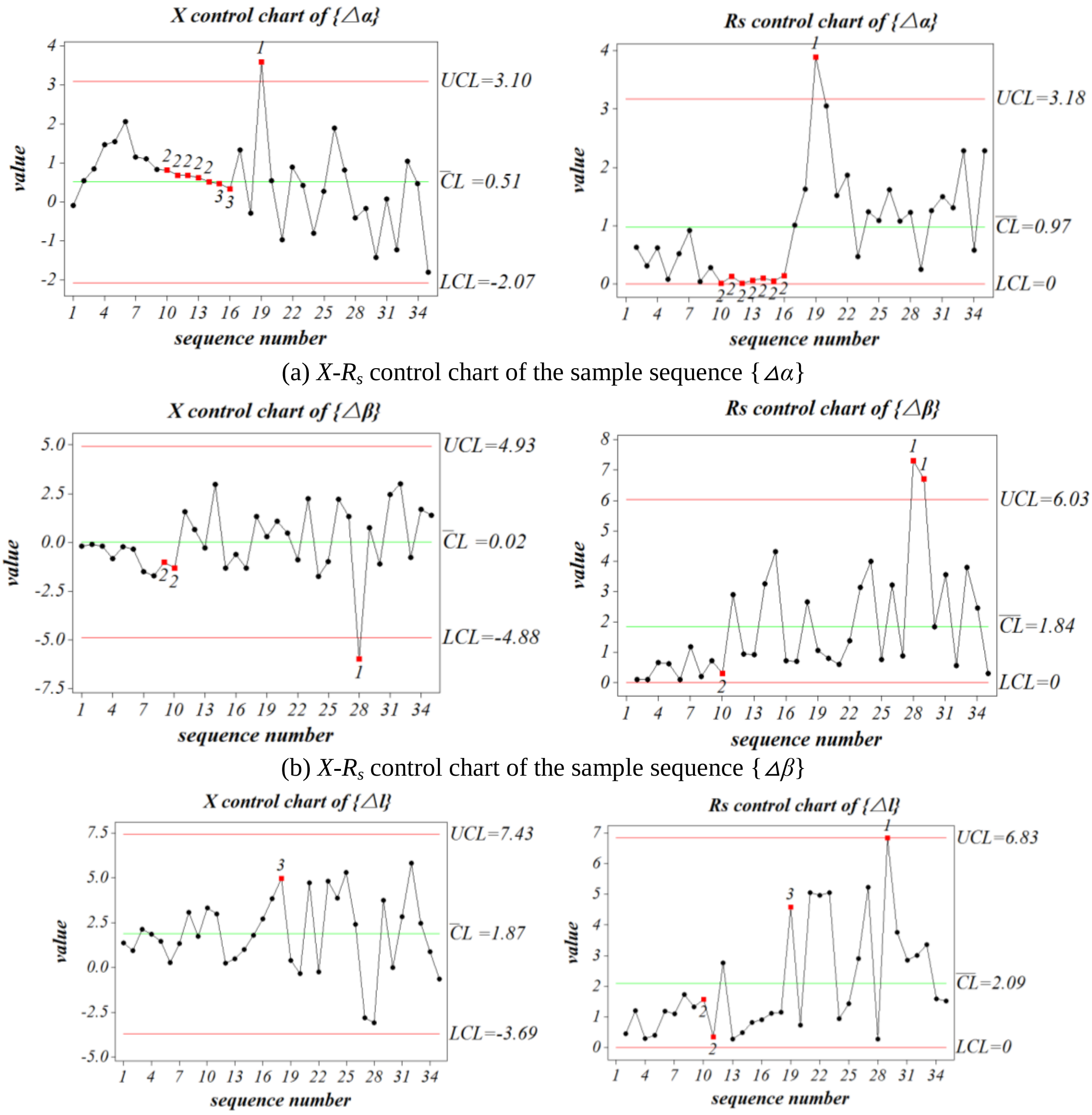
$$\begin{cases} \Delta\alpha \sim N(0.51,1.04) \\ \Delta\beta \sim N(0.02,1.74) \\ \Delta l \sim N(1.86,2.11) \end{cases} \qquad (6)$$

By comparison, measurement control chart X-R_s was appropriate for the process. Then UCL, CL and LCL of X-R_s control chart were respectively calculated as shown in Table.2.

Table.2 UCL, CL and LCL of inspection sample data

id	***Δα/°***		***Δβ/°***		***Δl/m***	
	X	R_s	***X***	R_s	***X***	R_s
UCL	3.10	3.18	4.93	6.03	7.43	6.83
CL	0.51	0.97	0.02	1.84	1.87	2.09
LCL	-2.07	0	-4.88	0	-3.69	0

Based on statistics of Table.2, X-$R_s$control charts were drawn as Fig.4.



(a) X-R_s control chart of the sample sequence $\{\Delta\alpha\}$

(b) X-R_s control chart of the sample sequence $\{\Delta\beta\}$

(c) X-R_s control chart of the sample sequence $\{\Delta l\}$

Fig.4 X-R_s control chart of the sample sequence

In Fig.4, red points mean anomalies. The NO.19 point of (a), the NO.28-29 points of (b) and the NO.29 point of (c) locate outside of UCL and LCL, and then warn break bound anomaly (type 1 anomaly). The NO.1-16 points of (a), the NO.1-10 points of (b) and the NO.1-10 points of (c) continuously locate in upside or downside of their CL, which forms chain anomaly (type 2 anomaly). The NO.6-16 points of (a) and the NO.12-19 points of (c) increasing monotonously means trend anomaly (type 3 anomaly).

When process status is in control, curve fluctuation should be random and slight around CL and between UCL and LCL. When three types of anomalies emerge, the process is beyond control. In view of above X control charts, break bound anomalies mean serious construction deviations from design, chain anomalies mean continuous construction deviations in the same direction from design, and trend anomalies indicate continuously increasing construction deviations in the same direction from design. In above R_s control charts break bound anomalies mean quick construction deviations from design, chain anomalies mean continuous too big or too small construction amplitude deviations in the same direction from design, and trend anomalies indicate continuously increasing construction deviation amplitude in the same direction from design.

Further on, we append those omitted inspection parameters into our research and track the process of coal and gas outburst prevention. An integrated and accurately quantized process control method, consisted of a series of control charts, was achieved.

Conclusion

By integrating statistical process control theory into study field of coal and gas outburst prevention, the following work was finished:

1) Inspection data series of coal and gas outburst prevention process. Based on two typical and wide-recognized techniques of coal and gas outburst prevention, process inspection data was classified into two categories, construction parameters and gas elimination parameters, and then was designed as a number of vectors.

2) Control charts. Based on the 3σ principle of statistical process control theory, statistical distribution and related statistics of the sample data were analyzed and then a series of X-R_s control charts was drawn for the studied process, which consists of elements such as data curves, UCL, CL and LCL and reflects process running statuses quantitatively.

3) Anomaly identification. In control charts, three types of anomalies, including break bound anomaly, chain anomaly and trend anomaly indicate different process running statuses. By tracking characteristics of control charts, every anomaly could be identified timely.

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References:

D.C. Montgomery. Statistical quality control: a modern introduction (6th ed.). John Wiley & Sons, 2008.

D.D. Song, Z.H. Ren, Y.X. Gu. Design and implement of an intelligent coal mine monitoring System. 8th International Conference on Electronic Measurement & Instruments, Aug. 16-18, 2007, Xian, China.

H.F. Wang, Y.P. Cheng, S.J. Hou, et al. Application of continuously pressure-relieving technology on long-distance upper protected seam of inclined coal seams. Journal of Mining & Safety Engineering, 2010, 27(2):210-214.

I.B. Shirokov, N.V. Koval, E.V. Koval. Microwave control system of state change of gaseous atmosphere in mines. 20th International Crimean Conference Microwave and Telecommunication Technology, Sep. 13, 2010, 1081-1082.

J.H. Fu. Recent situation analysis of Chinese coal and gas disasters: theoretical study and engineering practice of coal and gas prevention and control. Xuzhou: China University of Mining and Technology Press, 2005.

J.T. Guo. Monitoring and supervision system underground coal mine, Coal Technology, 2009, 28(6):97-99

J.Y. Jiang, Y.P. Cheng, H.F. Wang, et al. Effect of igneous intrusion on adsorption characteristics of coal to gas, 2012, 29(1): 118-123.

L.J. Ma. Study on gas abnormal emission dynamic response mechanism and disaster control technology. Master's Thesis of China Coal Research Institute, 2009.3.

L. Liu, F.B. Zhou. A comprehensive hazard evaluation system for spontaneous combustion of coal in underground mining. International Journal of Coal Geology, 2010, 82: 27-36.

Ms. Warsha, M. Choudhari. An intelligent coal mine security system using multi-view method. International Journal of Advanced Engineering Sciences and Technologies, 2011, 3(1): 15-19.

P.W. Shi. Developing scientific monitoring system for prohibiting disastrous accidents in mine. Journal of China Coal Society, 2002, 27(3): 225-228.

R. Balusu, P. Humphries, H. Guo, et al. Mine gas control technologies and practices in Australia. 2007 International Symposium on Coal Gas Control Technology, October 25-28, 2007, Huainan, Anhui, China, 106-120.

S.J. Hou, Y.W. Zhang, Y.P. Cheng. A computer aided design and simulation system for upward cross-seam boreholes. Journal of Applied Sciences, 2013, 13: 2538-2543. DOI: 10.3923/JAS.2013.2538.2543.

S.J. Hou, Y.W. Zhang. A novel algorithm for the coverage homogeneity analysis of along-seam boreholes in the coal gas drainage project. Energy Education Science and Technology Part A: Energy Science and Research, 2013, 31(3): 1803-1812.

S.J. Hou, J.Y. Liu, Y.W. Zhang. Development of boreholes construction deviation tracking software system: BCDTracking. Information Technology Journal, 2013, 12(19): 4918-4924, doi: 10.3923/itj.2013.4918.4924.

State Administration of Work Safety (SAWS). Coal and gas outburst prevention regulations, 2009. Available from: http://www.chinacourt.org/law/ detail/2009/05/id/136150.shtml. [Accessed May 10, 2014]

State Administration of Work Safety. NO.(2011)163 instruction, Gas extraction provisional regulations for coal mine. Beijing: China coal industry publishing house; 2011.

Y.P. Cheng, J.H. Fu, Q.X. Yu. Development of gas extraction technology in coal mines of China. Journal of Mining & Safety Engineering, 2009(26): 127-139.

Y.P. Cheng, Q.X Yu. Development of regional gas control technology for Chinese coal mines. Journal of Mining & Safety Engineering, 2007, 24(4): 383-390.