Paper No. 89

ISMS 2016

Numerical modelling and rescaled range analysis on spontaneous combustion under surface methane drainage in a Chinese coal mine

Xincheng Hu [a,b,c], Shengqiang Yang [a,b,*], Wei Victor Liu [c], Jiawen Cai [a,b], Xiuhong Zhou [a,b]

[a] School of Safety Engineering, China University of Mining and Technology, Xuzhou, China, 221008
[b] Key Laboratory of Gas and Fire Control for Coal Mines, Xuzhou, China, 221008
[c] Department of Civil & Environmental Engineering, University of Alberta, Edmonton, Canada, T6G 2W2

ABSTRACT
In China, surface boreholes have frequently been used to drain methane/gas emitting from overlying layers and longwall mining gobs in underground gassy coal mines. In this work, a numerical model was established using COMSOL TM to study the influence of surface drainage boreholes on coal spontaneous combustion and Rescaled Range Analysis (R/S analysis) was employed to investigate the chaos characteristic of Nitrogen (N_2)/Oxygen (O_2) drained from the gob. The simulation results show that there is a circular "dissipation zone" around the drainage borehole all the time and an elliptic "spontaneous combustion zone" when the borehole is located in deep gob. It is also found that the advancement of drainage boreholes has little influence on spontaneous combustion zones on the intake side of the gob but it can tremendously enlarge the width of a "spontaneous combustion zone" in the middle gob and reduce the depth of self-heating zones near the return side. The R/S analysis indicates that the influence of surface boreholes on spontaneous combustion can be divided into two stages: the safety drainage stage (Hurst index > 0.85) and the spontaneous combustion initiating stage (Hurst index≤ 0.85). It can be concluded that the gas drainage from gob through surface boreholes can tremendously intervene spontaneous combustion "three zones" in gob. In addition, the length-fixed R/S analysis on N_2/O_2 series from surface boreholes can effectively reflect coal spontaneous combustion conditions in gob.
KEYWORDS: Coal spontaneous combustion; surface drainage borehole; Hurst index; R/S analysis

1. INTRODUCTION

Coal spontaneous combustion has long been one of the most serious disasters in underground longwall coal mines, especially in the working face gobs (Ham, 2005). In China, about 32% of underground coal mines are spontaneous combustion prone and highly gassy (high methane content), which may cause severe disasters, especially when mining goes increasingly deeper (Zhou et al., 2013).

In highly gassy coal mines, methane drainage must be carried out before or along with mining. However, improper gas drainage may induce coal spontaneous combustion, leading to disastrous methane combustion and even explosions. In spite of long-time research on coal spontaneous combustion and methane prevention (Song and Kuenzer, 2014), few recent studies have addressed the severe threat of the combined effects of methane and coal spontaneous combustion (Madeja-Struminska and Widzyk-Capehart, 2006).

Although much research has focused on fracture development and gas migration after mining, little attention has been paid to coal spontaneous combustion caused by methane drainage. The 10416 working face in Yangliu Co.ltd., Huaibei, Anhui Province, China, was chosen to investigate the influence of surface methane drainage on coal spontaneous combustion in gob. COMSOLTM was adopted to simulate the influence of surface drainage boreholes on coal spontaneous combustion in gob. The chaos characteristic of N2/O2 indicator series collected from one surface borehole was analyzed using Rescaled Range Analysis (R/S analysis). The risk of coal spontaneous combustion in 10416 working face gob was divided and the corresponding critical values were confirmed in the end.

2. WORKING FACE DESCRIPTION

Coal 10, with an average distance of 74 m, 81 m, and 106 m from overlying coal 8_2, 8_1, and 7_2, is mined in 10416 working face. As the middle coal seams (7_2, 8_1 and 8_2) are coal and gas outburst prone, it serves as the remote protective layer for these three middle coal seams. In order to control the methane in the middle coal seams and the gob, surface drainage boreholes were drained before the advancement of 10416 working face to extract methane relieved from overlying methane-bearing strata and the longwall face gob.

As seen in Figure 1, the surface boreholes were located at the middle of working face, 70 m from the return tunnel in the dip direction. The surface drainage holes were drilled to the gob of the face, with an opening diameter of 311 mm and a final

*Corresponding author – email: ShengqiangYang@hotmail.com

diameter of 91 mm. To guarantee long-term extraction effect, the interval was set as 120 m.

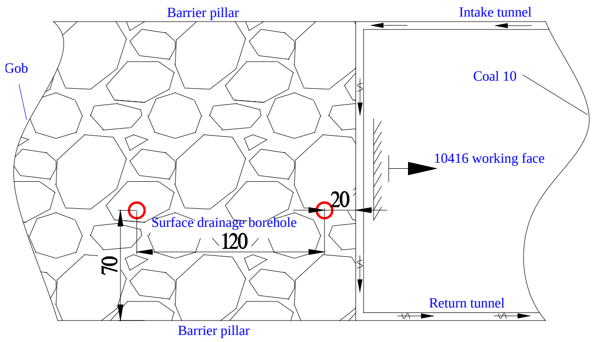


Figure 1: Tunnel arrangement of 10416 working face, Yangliu coal mine (units are in meters)

3. THE INFLUENCE OF SURFACE METHANE DRAINAGE ON COAL SPONTANEOUS COMBUSTION IN GOB

3.1 Modelling of 10416 working face gob

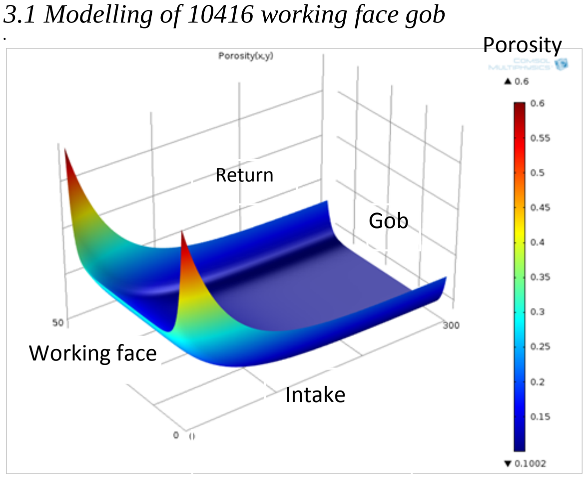


Figure 2: Porosity distribution in 10416 gob area

The height of the fractured zone can be confirmed as 35 m according to the empirical formula used by other researchers (Yang et al., 2011). The 10416 working face gob is slightly affected by the gas that might emit from the middle coal seams because of the long distance to coal 10 (Szlazak, Obracaj et al., 2014). Due to the remoteness of gas-bearing coals, the simulation model of 10416 working face gob can be simplified as a two-dimensional model, as previous researchers have done (Yuan and Smith, 2007).

As the porosity is dustpan– shaped in gobs (Li, Wu et al., 2008), the porosity distribution in 10416 working face gob can be estimated (Figure 2), and is highly permeable along the boundary with low–permeability in the middle and deep gob. There is a relationship between porosity and permeability in the gob, according to the Carmon equation:

$$k = \frac{D_p^2}{150}\frac{n^3}{(1-n)^2} \tag{1}$$

Where k is the permeability in the gob, m^2; n is the porosity in the gob, m; D_p is the average particle diameter in the gob, m. In order to simulate flow field in the gob, the boundary conditions were confirmed as per the practical parameters of 10416 working face as shown in Table 1.

Table 1: The boundary conditions of 10416 working face

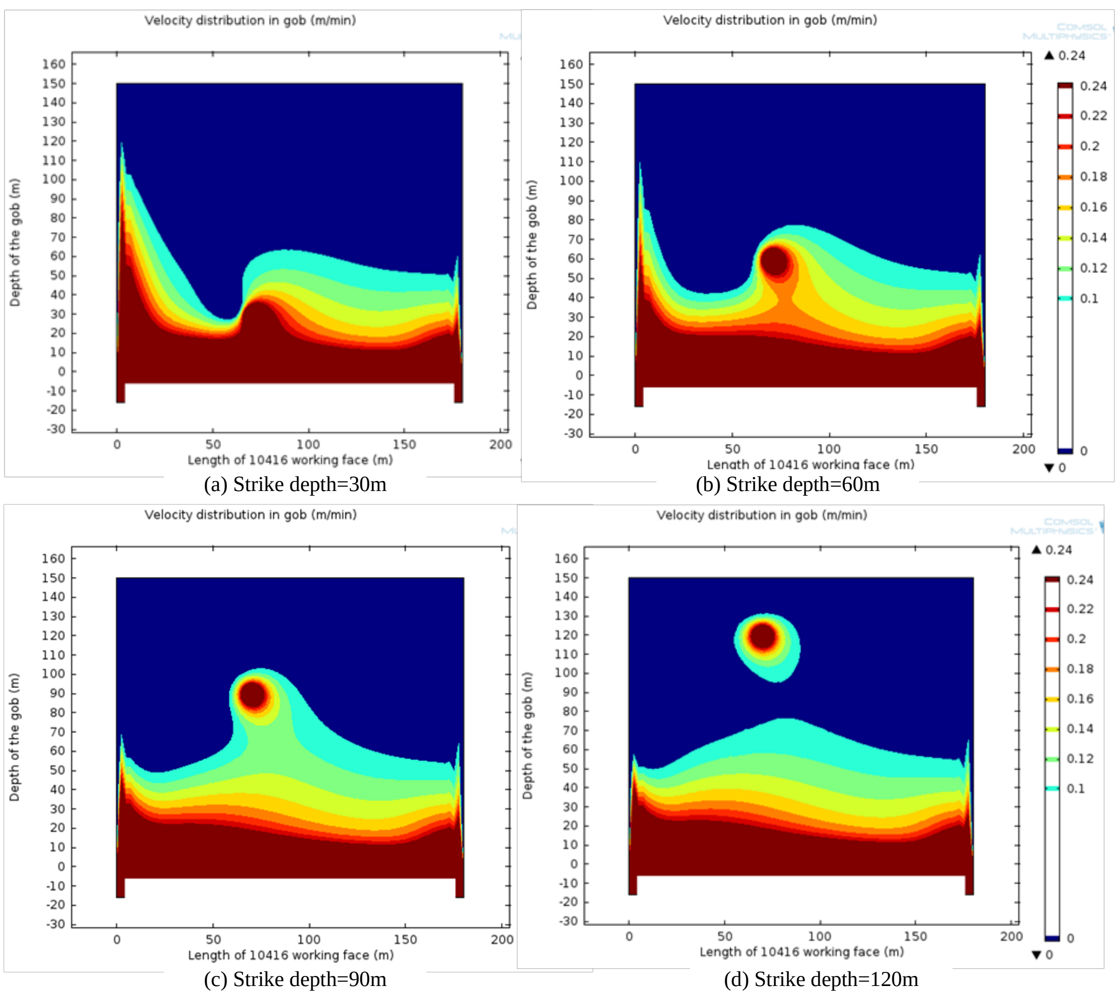
Site	Size	Flow	Boundary
Intake tunnel	4 m×10 m	Free flow	Pressure (0 Pa)
Return tunnel	4 m×10 m	Free flow	Velocity (2.1 m/s)
Working face	180 m×2 m	Free flow	/
Supporter area	180 m×4 m	Free flow	/
Gob	180 m×150 m	Porous flow	/
Surface borehole	91 mm (diameter)	Free flow	Velocity (0.5 m/s)

Although there are three main criteria (O_2 concentration criteria, flow velocity criteria, and temperature rate criteria) in determining “spontaneous combustion zone”, flow velocity criteria was chosen to indicate the self–heating danger in gobs because of the arduousness in simulating O_2 concentration distribution and heat field in gobs. It is recognized that if the flow rate in a gob is between 0.1 m/min and 0.24 m/min, the site is in a spontaneous combustion area. As the gob has been seen as porous media (Karacan et al., 2007), the Free and Porous Media Flow Model was chosen in COMSOL^{TM} to simulate the influence of surface methane drainage on “three-zone” distribution in the gob.

3.2 The influence of surface drainage borehole on “three zones”

Methane can be drained by surface drainage boreholes, thus tremendously disturbing the airflow distribution. Figure 3 describes the distribution of three zones in the gob with different strike depths of surface drainage boreholes. Overall, the influence is more obvious on the return side of the gob than the intake side. There is a circular dissipation zone around the borehole during the whole extraction process and an elliptic ring-sized spontaneous combustion zone when the borehole reaches the deep gob. With the movement of boreholes to deeper gobs, the spontaneous combustion zone near the return side advances toward the face while the dissipation zone narrows. By contrast, the impact on the intake side is smaller compared with the return side. However, the spontaneous combustion zone near the borehole is reduced at the beginning and then broadened with the increasing depth.

The spontaneous combustion zone is encroached by both the dissipation zone and the suffocation zone, owing to the drainage effect of the surface borehole in shallow gobs (around 30 m). When the location of the borehole approaches the middle gob (around 60 m), there is a round dissipation zone around the drainage hole. The width of the self –heating zone near the intake side of the drill is increased whilst the depth along the return roadway is reduced. With the further advancement of the face (about 90 m), the influence of the surface borehole enlarges. The spontaneous combustion zone near the drill is drained to deeper gob with greater width, but the width along the return roadway is shortened. When the borehole goes deeper (120 m), an elliptic ring–shaped spontaneous combustion zone emerges. As a result, the gob along the moving route of the drill is more dangerous than other area in gob because of the enlarged spontaneous combustion zone and the long–lasting elliptic self –heating zone around the drill. Due to the complexity of methane drainage through surface boreholes, the prediction of the coal spontaneous combustion condition in gobs is of great importance.



(a) Strike depth=30m (b) Strike depth=60m

(c) Strike depth=90m (d) Strike depth=120m

Figure 3: The influence of strike location of surface drainage borehole on spontaneous combustion in gob

4. COAL FIRE PREDICTION DURING METHANE DRAINAGE

4.1 Chaos characterisation

Rescaled range analysis (*R/S* analysis) is widely employed to scale the chaos characteristic of time series. As chaos is pervasive in engineering, gas indexes from surface boreholes are no exception. The relationship between R and S accords with the formula below (Zhu and Ji, 2011):

$$R/S=(\alpha\tau)^H \tag{2}$$

Where R is the extreme range of the time series, S is the standard deviation of the time series, R/S is the rescaled range, τ is the observational frequency, α is a constant value, H is Hurst index. It has been proven that if $0.5<H\leq1.0$ the time series is a growing series, implying the future can be reflected by the present (Falconer, 2013).

4.2 Chaos characteristic of the indicator for coal spontaneous combustion

Considering the influence of methane emission and CO_2 injection, most gas indexes including single gas indexes and Graham ratios are not inapplicable in predicting coal spontaneous combustion in gobs, while the N_2/O_2 ratio is an exception (Hu, Yang et al. 2015). Gas samples were gathered from a surface drainage borehole every four hours i.e. two samples every shift. As showed in Figure 4, a total of 218 N_2/O_2 ratios were collected on the ground during methane draining.

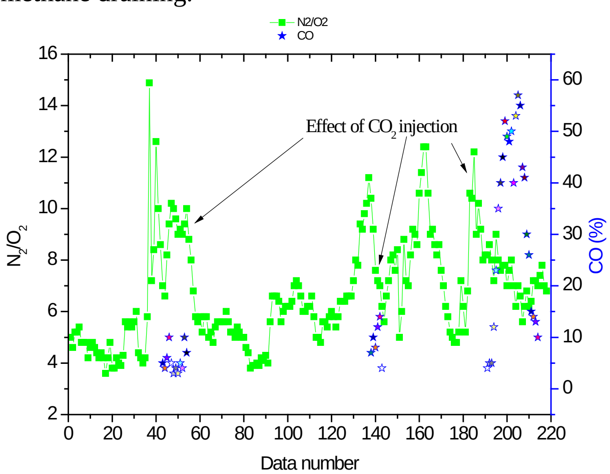


Figure 4: The variation of N_2/O_2 ratio during methane draining from surface boreholes

During the whole draining process, the N_2/O_2 ratio fluctuated up and down. If the N_2/O_2 soared up, CO ensued. Owning to the cooling and stifling effect of CO_2 on self –heated coal, the N_2/O_2 ratio descended and CO faded away.

4.3 Chaos characteristic of N_2/O_2 time series

Figure 5 shows that the Hurst value gradually levels out around 0.9, showing a stable chaos characteristic. Setting the observation frequency as 80, the length-fixed time series can be employed to weigh the spontaneous combustion condition in gob as shown in Figure 6.

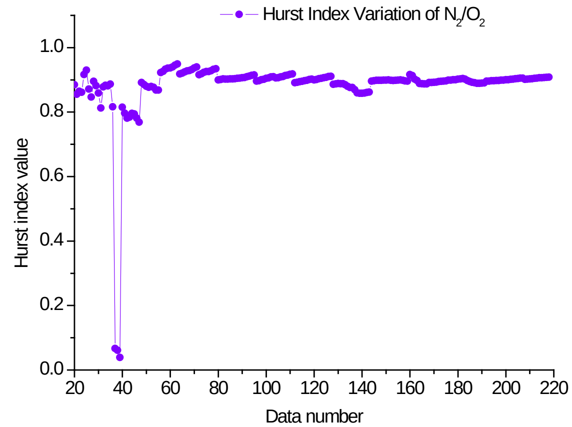


Figure 5: Hurst index variation of N_2/O_2 with data number

It is apparent that whether or not CO was detected, the Hurst value fluctuates between 0.5 and 1. At first, when CO was not detected or in low concentration, the ratio fluctuates regularly. Although CO_2 was injected when CO was detected, the value is still larger than 0.8, showing a stable chaos characteristic. However, a dramatic decline is observed and relatively higher CO concentration follows owing to the deeper oxidation of coal in gobs. Depending on a certain length of statistical data, the influence of seldom abnormal value can be avoided. Therefore, the Hurst value is more stable and misinformation can be eliminated.

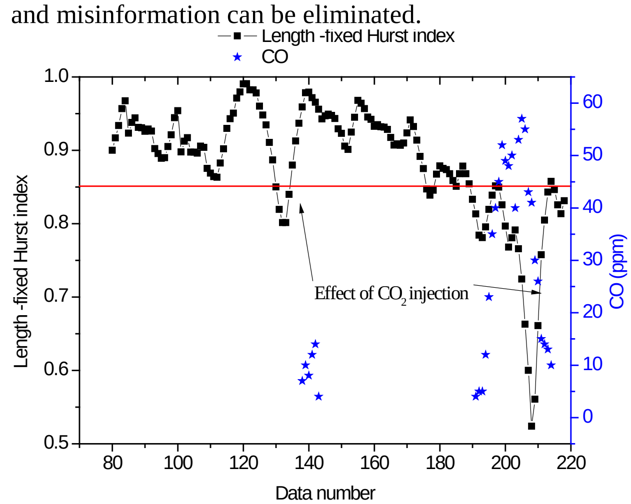


Figure 6: Variation of length–fixed Hurst index and CO

4.4 Critical values

Fixing the length of the N_2/O_2 time series to 80, the risk of surface methane drainage in the working face gob can be divided into two stages based on the aforementioned analysis:

(1) Safety drainage stage (Hurst index>0.85)

Pursuant to the analysis above, 0.85 is the lowest value under normal condition when there was no CO, indicating that the oxidation condition of coal in 10416 working face gob was in low-temperature oxidation stage.

(2) Spontaneous combustion initiating stage (Hurst index≤0.85)

Similarly, if the Hurst value of N_2/O_2 in surface borehole is lower than 0.85, the oxidation of coal in gob is accelerated. The smaller the Hurst index the deeper the oxidation of coal.

5. CONCLUSIONS

This paper highlights the influence of surface drainage boreholes on coal spontaneous combustion by COMSL™ simulating and coal spontaneous combustion predicting possibility employing R/S analysis. Several conclusions can be made as follows:

(1) In the vicinity of the working face, the methane drainage can narrow the width of spontaneous combustion zone around the borehole, whilst deeper strike depth leads to a wider spontaneous combustion zone in the middle gob with the advancement of the borehole.

(2) The advancement of the surface drainage borehole has little effect on the spontaneous combustion zone on the intake side but it reduces the depth of the self -heating area dramatically on the return side.

(3) N_2/O_2 time series has a chaos characteristic. The risk of coal spontaneous combustion in 10416 can be divided into two stages: the safety drainage stage (Hurst index>0.85) and the spontaneous combustion initiating state (Hurst index≤0.85).

6. ACKNOWLEDGEMENTS

This work was conducted in the context of coal spontaneous combustion control in Yang Liu Co.ltd and financially sponsored by the National Natural Science Foundation of China (51174198), the State Key Laboratory of Coal Resource and Safety Mining, China University of Mining and Technology (SKLCRSM11X01) and CSC (China Scholarship Council). The authors wish to express their gratitude to the sponsors and especially to the staff of the YangLiu Mining Co. Ltd.

7. REFERENCES

Falconer, K. (2013). Fractal geometry: mathematical foundations and applications, John Wiley & Sons.

Ham, B. (2005). A review of spontaneous combustion incidents. COAL 2005: 6th Australasian Coal Operators' Conference. 2005: 237-242.

Hu, X., S. Yang, X. Zhou, Z. Yu and C. Hu (2015). "Coal spontaneous combustion prediction in gob using chaos analysis on gas indicators from upper tunnel." Journal of Natural Gas Science and Engineering 26: 461-469.

Karacan, C. "A new method to calculate permeability of gob for air leakage calculations and for improvements in methane control."

Li, Z.-x., Q. Wu and Y.-n. Xiao (2008). "Numerical simulation of coupling mechanism of coal spontaneous combustion and gas effusion in goaf." JOURNAL-CHINA UNIVERSITY OF MINING AND TECHNOLOGY-CHINESE EDITION- 37(1): 38.

Madeja-Struminska, B. and E. Widzyk-Capehart (2006). Correlation between methane and fire hazards in abandoned workings of longwall mining. 11th U.S./ North American Mine Ventilation Symposium 2006: 325-330.

Song, Z. Y. and C. Kuenzer (2014). "Coal fires in China over the last decade: A comprehensive review." International Journal of Coal Geology 133: 72-99.

Szlazak, N., D. Obracaj and J. Swolkien (2014). "Methane drainage from roof strata using an overlying drainage gallery." International Journal of Coal Geology 136: 99-115.

Yang, W., B. Q. Lin, Y. A. Qu, S. A. Zhao, C. Zhai, L. L. Jia and W. Q. Zhao (2011). "Mechanism of strata deformation under protective seam and its application for relieved methane control." International Journal of Coal Geology 85(3-4): 300-306.

Yuan, L. and A. Smith (2007). "Computational fluid dynamics modeling of spontaneous heating in longwall gob areas." transactions-society for mining metallurgy and exploration incorporated 322: 37.

Zhou, F.-B., T.-Q. Xia and B.-B. Shi (2013). "Coexistence of gas and coal spontaneous combustion (II): New prevention and control technologies." Meitan Xuebao/Journal of the China Coal Society 38(3): 353-360.

Zhu, H. and C. Ji (2011). Fractal Theory and Its Applications. Beijing, Science Press.