Article ID: 1003 - 6326(2000)02 - 0284 - 04

Chaos dynamic characteristics during mine fires①

ZHONG Mao-hua(钟茂华)[1], CHEN Bao-zhi(陈宝智)[2],
FAN Wei-cheng(范维澄)[1], WANG Qing-an(王清安)[1]
1. State Key Laboratory of Fire Science,
University of Science and Technology of China, Hefei 230026, P. R. China;
2. Department of Safety Engineering, School of Civil Engineering,
Mail Box 265 Northeastern University, Shenyang 110006, P. R. China

Abstract: Mine fires break out and continue in confined scopes, studying mine fire dynamics characteristics is very useful to prevent and control fire. The judgement index of fire chaos characteristics was introduced, chaos analysis of mine fire process was described, and the reconstruction of phase space was also presented. An example of mine fire was calculated. The computations show that it is feasible to analyze mine fire dynamic characteristics with chaos theory, and indicate that fire process is a catastrophe, that is to say, the fire system changes from one state to another during mine fire.

Key words: mine fire; dynamic characteristics; state change **Document code: A**

1 INTRODUCTION

Mine fire is one of the critical disasters in underground coal mining[1]. Once fire accidents happen, they cause a large loss of livers, destroy generous coal resources and equipment. If they are not handled properly and timely, they maybe induce more serious consequences such as gas or/and dust combustion and explosion leading to the further expansion disasters. According to differences of fire causing, the mine fires are divided into two types, breeding fire and exogenous one[2,3].

Mine fires break out and continue in confined scopes where the ventilation network is very complicated. They have their own characteristics during their starting, propagating, and fire fighting[4,5]. The burning objectives of mine fires are different from those which are obvious in the surface. The toxic and high temperature fumes produced during mine fire are fairly dangerous, in the meantime, the density of O_2 declines quickly, so miners who inhale polluted air can be poisoned and even die. Fire flame reduces visibility to shelters and itineraries for avoiding fire, at the same time, they hinder miners from evacuating fire zones and fire fighting. Moreover, thermodynamics effects of high temperature airflow disorder mine ventilation systems, when fire scopes attain some extents, air quantities of galleries decrease quickly, even cause the reversals of airflow directions in some airways so that the spread scopes of fire fumes may be expanded[6,7].

In some reports and statistical figures, 95 % of those who were killed by mine fires resulted from toxic fumes[5,8~10]. Sometimes mine fires cause coal-dust and gas explosives so that fire risks and scopes may be enlarged. This is one of the main reasons that mine fires are very dangerous to miners[11~13]. So, studying mine fire dynamics characteristic is very useful to prevent and suppress mine fire.

In this paper, we used deterministic chaos to analyze the formation, happening and development of mine fire, and to study system state changes.

2 ANALYSIS METHODS

Output information, such as pressure, temperature and velocity, is very helpful to analyze mine fires. Using time series of these variables, we can investigate the fire consequence. Extracting mine fire characteristics from variables of time series is useful for us to comprehend and understand continuous changes of accident procedure, and system states catastrophes. How to survey fire dynamic characteristics using one or more variables of time series is the key to understand the fire process. Deterministic chaos theory is conductive to the solutions of the problem, it can extract dynamic behaviors from a variable of time series. Analyses methods of chaos mainly include: 1) reconstruction attractor of phase space from time series, the attractor represent system dynamic behaviors[14,15]; 2) based on time series calculation of Kolmogorov entropy and fractal dimension which are important measurement of chaos states in phase spaces[16].

2.1 Reconstruction attractor of phase space from time series

Supposing an output variable of system is $\{v_j\}$,

① **Foundation item:** Project 59776018 supported by the National Natural Science Foundation of China
Received date: Apr. 26, 1999; **accepted date:** Dec. 14, 1999

using (n, J) window we can construct vectors x_i,

$$x_i = (v_i, v_{i+j}, \cdots, v_{1+(n-1)J})^T \quad (1)$$

The application of an $(n, 1)$-window to a time series of N_T datapoints results in a sequences of $N = N_T - (n-1)$ vectors, $\{x \in \mathbf{R}^n | i = 1, 2, \cdots, N\}$ in the embedding space. Based on Takens' Theorem, such a sequence can be used to construct a trajectory matrix, $\mathbf{Y}$, here

$$\mathbf{Y} = \{x_1, x_2, \cdots, x_N\} \quad (2)$$

State trajectory reconstructed remains some major characteristics of former trajectory. A time series of measurements made on a system, $\{v_j\}$, must be disturbed by some noise. Researches show that noise weakens deterministic characteristics of mine fire output information. In different bases of $\mathbf{R}^n$, effects of noise different. As the embedded space is multi-dimension, it is very difficult to plot its attractor by using common geometry methods. So we should determine the problem that which basis the plane is made from can correctly reflect system characteristics.

The trajectory matrix X is

$$X = N^{1/2}[x_1^T, x_2^T, \cdots, x_N^T] \quad (3)$$

Using trajectory matrix, the covariance matrix, Ξ, is shown in the following,

$$\Xi = X^T X = \frac{1}{N}\sum_{i=1}^{N} x_i x_i^T \quad (4)$$

where Ξ is a real, symmetric $n \times n$ matrix, and corresponding to a quadratic form. A real and quadratic form can be exchanged into a standard form using linear change of full rank. From the eigenvectors of the standard form, we can induce a set of orthogonal basis which can be embedded in $\mathbf{R}^n$. We project attractor onto the plane spanned by the two eigenvectors which are corresponding to the two biggest characteristic values, and the plots contain main dynamic characteristics of system. This is the reason that geometric shape of the attractor in the plane is the biggest, and the effect of noise is little in the directions of the two eigenvectors. In practice, a bigger n is used, then a lesser n can be gained using characteristic values spectra.

2.2 Computation of Kolmogorov entropy of chaotic information

Kolmogorov entropy is one of important measurements of chaos, and using it regular movements, chaos movements, and random movements can be distinguished. The computation of Kolmogorov entropy is related to correlation dimension.

The correlation dimension is defined as follows:

$$D = -\lim_{r \to 0}[\ln C_n(r)/\ln r] \quad (5)$$

$$C_n(r) = \frac{1}{N^2}\sum_{i,j}^{N} H\{r - \| x_i - x_j \|\} \quad (6)$$

where $H\{\cdot\}$ is Heaviside function, and $\|\cdot\|$ is norm. So Kolmogorov entropy, K_2, is in the following

$$K_2 = \lim_{\substack{r \to 0 \\ n \to \infty}}\left[\frac{1}{j}\ln\frac{C_n(r)}{C_{n+1}(r)}\right] \quad (7)$$

where $C_n(r) \simeq r^D \exp(-nJK_2)$, $n \to \infty$, $r \to 0$. K_2 is one of important measurements of chaos. K_2 is ∞ in random system, but in regular movements $K_2 = 0$, and in chaos system $K_2 > 0$. The larger K_2 is, the more chaos characteristic of fire system is[6].

3 EXAMPLE ANALYSIS OF MINE FIRE

An example of mine fire is given in the following. At the 660 m mark, the drivage struck the goaf of old stall and heading workings in a seam, which was 84 cm thick, with a strong shale roof and hard fireclay floor. The old workings were passed through in a total distance of 109.73 m and the old roads were filled with rubbish for approximately 1.8 m on either side of the drivage, where timber cogs were erected for extra support. In the length of roadway that passed through the seam goaf, it was expected that there would be an in-leakage of air from the west return through the old workings; in fact some 8.49 ~ 9.43 m^3/s entered the heading. After ten days methane was ignited and the mine fire continued in the colliery. During the period of fire fighting, some attempts to control the fire by sealing the area and using airlock were unsuccessful. Finally, mine fire was eliminated with nitrogen gas.

Using the above methods, we select two time series of $[CH_4]$ and $[O_2]$ to analyze the fire. The time series are illustrated in Fig.1. First, the phase space dimension must be determined, so 4 observing windows, which are (15,1), (20,1), (25,1) and (30,1), are used to calculate the character values spectra of time series of $[CH_4]$ and $[O_2]$. Based on their spectra, the embedded space dimensions of $[CH_4]$ and $[O_2]$ are 7, 8 respectively. The correlation fractal dimensions of $[CH_4]$ and $[O_2]$ are 0.55 ~ 1.03 and 0.3 ~ 1.01 respectively. At the mean time, Kolmogorov entropy is larger than zero, so the catastrophic system of mine fire is a chaos system.

The two time series of $[CH_4]$ and $[O_2]$ are embedded into $\mathbf{R}^7$ and $\mathbf{R}^8$ respectively, their trajectories are projected onto plane spanned by vectors (C_1, C_2), which is corresponding to the two bigger character values, λ_1 and λ_2, of covariance matrix. The attractors are illustrated in Fig.2. Embedding exchange may change geometric shapes of attractors, but their dynamic characteristics can not be changed. So some conclusions reached are as follows:

1) The trajectory of fire procedure shows obvious chaos characters, and the attractor has global stability and local instability (or no periodicity). No periodicity shows that the system trajectory never intersects or overlaps at any time, so the attractor must be

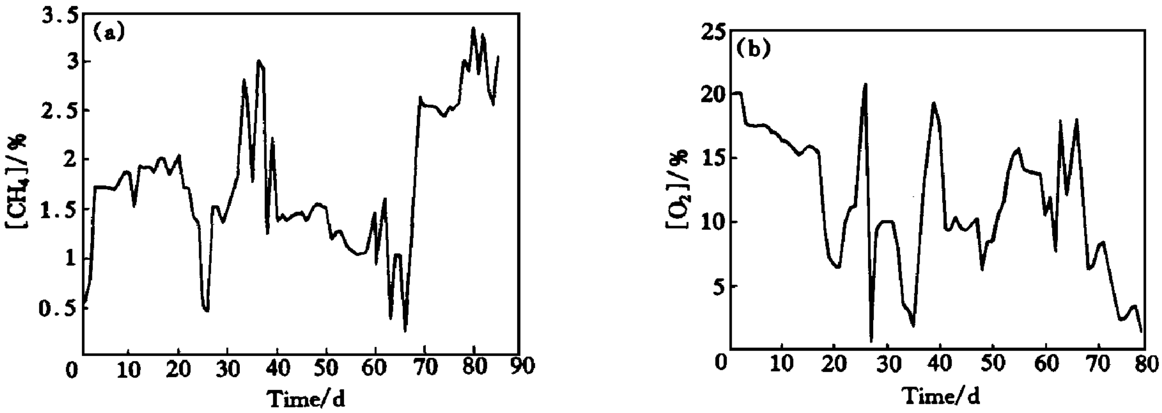

Fig.1 Time series of $[CH_4]$ (a) and $[O_2]$ (b) during mine fire

(a) —$[CH_4]$; (b) —$[O_2]$

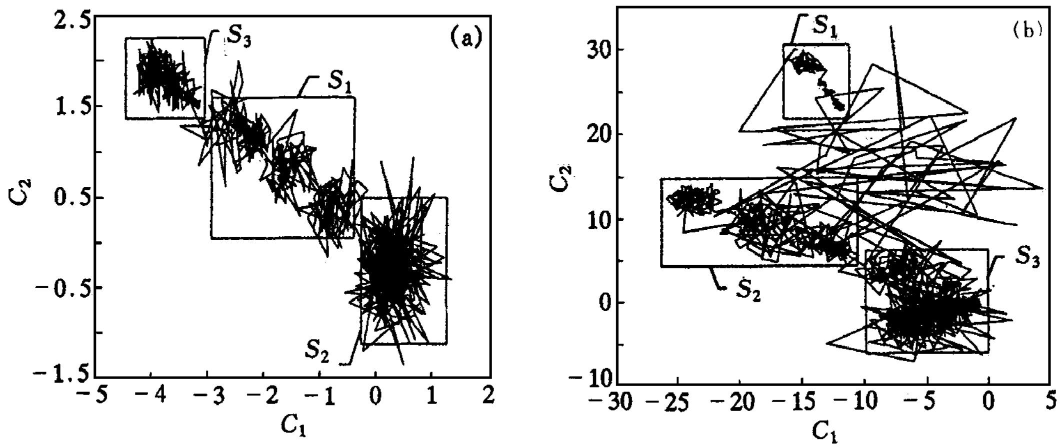

Fig.2 Plots of attractors ($[CH_4]$ (a) and $[O_2]$ (b)) projected onto plane spanned by (C_1, C_2) during mine fire

fractal. Fractal dimension is one of key measurements which can be used to describe mine fires. Simultaneously, no periodicity states that it is impossible to make long term forecast of mine fire accidents.

2) The dim area of attractor, which is surrounded in dotted lines, presents the states where system is preserved. In different times of mine fire, system states show catastrophic characters. At the beginning of fire, its state is S_1. With the fire expansion, its state is S_2. Once the fire is regulated and eliminated timely, its state is S_3. So the procedure of mine fire is catastrophe of mining system. Therefore, mine fire can be described in catastrophe models, and deterministic chaos theory can describe the changes of mine fire system among multi-states.

3) During the period of mine fire, the trajectory of system state is strongly dependent on the initial conditions, so we can not repeat one mine fire in laboratory or field completely[17]. Fire propagating characteristic curve is the output of fire zone, generally, the curve can be determined only after each fire process.

Using the proposed method, we also analyzed fire fumes of $[CO]$, $[CO_2]$ and $[H_2]$ in the mine fire, and make the same conclusions described above[6].

4 CONCLUSIONS

To study dynamical characteristics of mine fire using chaos is an attempt to explore the catastrophe laws of mine fires. From the analysis above, the following conclusions can be reached.

1) Using chaos theory, we proposed chaos analysis of fire dynamics, and introduced fractal dimensions and Kolmogorov entropy to describe the change law of fire dynamics characteristic.

2) An example of mine fire was calculated using deterministic chaos analysis and the dynamic behaviors law was investigated.

3) Analysis proved that mine fire process shows chaos and fractal characteristic and is a catastrophe, so it is feasible to analyze mine fire based on fractal dimensions and catastrophe models.

ACKNOWLEDGMENTS:

This research was supported by China National High School Special Foundation for Doctoral Subject Study (96014505) and Key Program of the 9th Five-Year Plan of China (96-918-04-03).

REFERENCES

[1] WU Zhong-li. Mining Ventilation and Mine Safety [M], (in Chinese). Xuzhou: China University of Mining and Technology Press, 1989.

[2] XU Jing-cai, WEN Hu and GAO Xing-ming. On index of self-combustion tendency of coal by spontaneous combustion experiment [J]. Journal of Xi′an Mining Institute, (in Chinese), 1997, 17(2): 103 ~ 107, 126.

[3] ZHONG Mao-hua, WEN Li-min, CHEN Bao-zhi, et al. Analysis for catastrophe of mining atmospheric properties during fire [J]. The Chinese Journal of Nonferrous Metals, (in Chinese), 1998, 8(4): 729 ~ 733.

[4] ZHONG Mao-hua, CHEN Bao-zhi and XU Kai-li. Catastrophe Analysis of Coal Spontaneous Fire [J]. Journal of Northeastern University, (in Chinese), 1999: 20(1): 68.

[5] ZHONG Mao-hua, CHEN Quan and CHEN Bao-zhi. Fractal characteristics of mine atmosphere during fires [J]. Journal of China Coal Society, (in Chinese), 1998, 23(1): 58.

[6] ZHONG Mao-hua. Study on Dynamics Characteristics and Optimal Control of Accident Process [D], (in Chinese). Shenyang: Northeastern University, 1998.

[7] ZHOU X Q and WU B. Theory and Application of Mining Fire Fighting [M], (in Chinese). Beijing: China Coal Industry Press, 1996.

[8] ZHONG Mao-hua and CHEN Bao-zhi. Application of catastrophe theory to mining safety [J]. China Safety Science Journal, (in Chinese), 1998, 8(1): 69 ~ 72.

[9] Greuer R. E. Study on mine fires and mine ventilation, Part 1 [A]. Computer Simulation of Ventilation Systems Under the Influence of Mine fires [R], USBM Contract No. S0241032, 1977.

[10] Greuer R E. Real time precalculation of the distribution of combustion products and other contaminants in the ventilation system of mines [R]. Mineral Research Contract No. J0285002, 1981.

[11] Matsuguma Kiso, Seisho Minoru, Isei Takehiro, et al. On the propagation of timber fire and the length of fire-break in full-scale test gallery [J]. Mining and Safety, (in Japanese), 1975, 21(3): 113 ~ 119.

[12] Perzak F J, Litton C D, Mura K E, et al. Lazzara, Hazards of conveyor belt fires [A]. Report of Investigation 9570 [R]. United States Bureau of Mines, 1995.

[13] WU Chou and Men T L. Theory and Application of Breeding Fire of Sulfur Mine, (in Chinese). Beijing: China Metallurgical Industry Press, 1995.

[14] Packard N H, Crutchfield J P, Farmer J D, et al. Geometry from a time series [J]. Physical Review Letters, 1980, 45(9): 712.

[15] Grassberger P and Procaccia I. Characterization of strange attractors [J]. Physical Review Letters, 1983, 50(5): 346.

[16] Broomhead D S and King G P. Extracting qualitative dynamics from experimental data [J]. Physica, 1986, 20D(2/3): 217.

[17] LI Hu-sheng. Simulation and Optimal Control of Airflow States Under Influence of Mine Fires [D], (in Chinese). Beijing: China University of Mining and Technology, 1995.

(Edited by HE Xue-feng)