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Intelligent safety adjustment of branch airflow volume during ventilation-on-demand changes in coal mines

Kai Wang[a,b,c,*], Shuguang Jiang[a,c,d], Zhengyan Wu[a,c], Hao Shao[a,c], Weiqing Zhang[d], Xiaodong Pei[a,c], Chuanbo Cui[a,c]

[a] Key Laboratory of Coal Gas and Fire Control, Ministry of Education, China University of Mining & Technology, Xuzhou, China
[b] School of Information and Electrical Engineering, China University of Mining & Technology, Xuzhou, China
[c] School of Safety Engineering, China University of Mining & Technology, Xuzhou, China
[d] State Key Laboratory of Coal Resources and Safe Mining, China University of Mining & Technology, Xuzhou, China

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ABSTRACT

In view of the frequent ventilation-on-demand (VOD) changes of branches during intensive production in coal mines, the models for regulating the ventilation resistance of associated branches and ventilator frequency were established. Automated ventilation system adjustment software has been developed by monitoring the air volume of the minimum remainder branch in the network, and all air volumes of the branches in the network can be obtained by inverse calculation of associated branches. When the VOD of branches changes, the best regulating branch in the ventilation network is selected by a cellular automation (CA) model, and the ventilation resistance is determined by ventilation network calculation. It is also possible to calculate the total air volume of the ventilation system, according the VOD of the branch to calculate the ventilator frequency. Advanced simulation regulating results are verified by ventilation network calculation. The ventilation resistance of associated branches, ventilator frequency, and joint regulation are simulated by the automated ventilation system adjustment software.

A pipe network ventilation parameter monitoring system is designed and developed based on typical ventilation network models. We confirm the VOD of the branch based on the absolute gas emission volume prediction model and then establish a regulating model for the ventilation resistance of associated branches and the ventilator frequency. Considering the fire and explosion risks associated with gas, CO_2 is instead released to simulate gas emission in the experiment; gas concentration is controlled by the ventilation resistance of associated branches and ventilator frequency. These results verify that CO_2 concentration is kept below the threshold value by increasing the air volume of the branch, the feasibility of the ventilation system, and regulating the VOD of the branch; additionally, they provide theoretical guidance for adjusting ventilation branch quantity by the association branches of ventilation resistance and ventilator frequency.

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* *Corresponding author at*: School of Safety Engineering, China University of Mining & Technology, Xuzhou 22116, China.
E-mail address: wangkai850321@163.com (K. Wang).
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1. Introduction

Coal is one of our most important energy resources and will remain so in the near future; in recent years, up to 70% of the energy consumption in China comes from coal (Liu and Harpalani, 2013; Liu et al., 2016; Wang et al., 2016a). However, underground coal mines are among the most dangerous working environments, because the presence of gas and coal dust can result in health issues for miners and/or explosions (Brake, 2002; Mitchell and Goddlad, 2012; Marzilger and Berthold, 2012). A good ventilation system is mandatory for ensuring a safe and productive environment in an underground coal mine (Petrov, 1997; Hamm and Sabet, 2010; Kozyrev and Osintseva, 2012). An efficient ventilation system provides fresh air, removes hazardous gases and dust, and maintains the temperature and humidity at appropriate levels (Torano et al., 2009; Plessis et al., 2013) revealed that up to 60% of the total mining operating costs is attributable to mine ventilation costs, given the vast quantity of electrical energy consumed to drive fresh air to various locations in underground coal mines.

With increasing energy costs and the implementation of carbon taxes in many countries, the development of a cost-effective mine ventilation system that ensures a safe and productive environment while minimizing energy usage and operating costs has become highly essential for the mining industry (Medved et al., 2012; Shonin and Pronko, 2013; Babu et al., 2015; Ordin and Metel'kov, 2013). As such, the concept of ventilation-on-demand (VOD) has received considerable attention. The idea behind this concept is straightforward: supply fresh air to a location only when it is needed. Applying this system in underground mines requires complex control systems and sophisticated monitoring devices as well as effective adjustment models and control theories (Tuck et al., 2006; Allen and Keen, 2008; O'Connor, 2008). Transient states in mine ventilation are caused by natural factors and usually happen at random, or occur because of changes in the operation of ventilation devices during adjustment or experiments (Kurnia et al., 2014a; Patel and Patel, 2012; Chatterjee et al., 2014; Shim et al., 2014).

Under certain conditions, transient states are characterized by sudden changes in gas emission, gas pressure, and flow conditions, often with large amplitude. In the presence of a gas concentration transfinite in a mining tunnel, the response is typically to increase the ventilation wind quantity in order to dilute the gas (Cheng, 2012). Predicting gas emission and discerning the emission law are the basis for effective control of gas concentration transfinite (Lu et al., 2016). Research in Russia promoted global technological progress in gas emission prediction (Connell et al., 2010). Transient states with the properties specified above are particularly likely to occur during ventilator frequency adjustment, with mine characteristics changing because of the opening and closing of the air doors (Vaneev and Goryagin, 2010; Tuck et al., 2006; Widodo et al., 2008).

Observations of these transient states and their consequences in an actual mine ventilation system had previously been impossible because of the lack of appropriate control and measurement equipment. Only the use of data recorded in mine monitoring systems (Dziurzyński et al., 2010; Wang et al., 2016b) and specialist equipment allowed for recording air parameters during such experiments on the scale of the entire mine. Using the mine monitoring system, pressure during excavations and airflow velocity can be registered. Another interesting main ventilator stoppage experiment took place in the Żory mine (Özgen Karacan et al., 2012). Its aim was to observe, using the monitoring system and specialized equipment in the mine, changes in air parameters such as pressure, airflow direction, and gas concentration. However, working areas in underground mines have become further and deeper from inlets and exhaust shafts (Wang et al., 2015). A reasonable ventilation network offers long-term benefits to mine safety and economics. Studies on mining safety, including field investigation, numerical simulation (Torro et al., 2015; Wang et al., 2016c) and laboratory experiments (Packham et al., 2012) have also improved over the past decade. Through the analysis of existing solutions, a real-time solution of a mine ventilation network was proposed. Wei et al developed a windows-based ventilation network visualization management system (Wei et al., 2008, 2010 Zhu et al., 2009). However, intelligent mine ventilation control and branch volume adjustments using ventilation network calculations, as well as mine ventilation monitoring systems and abnormal branch airflow causality analyses have not been as thoroughly researched (Kurnia et al., 2014b; Ordin et al., 2015).

Therefore, faced with the above problems, to improve the efficiency of the mine ventilation intelligent control system, we aim to enhance the reliability of the ventilation system. In the abnormal situation of having multiple branches in the ventilation system, if there is a non-variable-frequency sensitive branch, then variable-frequency ventilator regulations cannot meet airflow volume requirements. We aim to increase methods of branch regulation, study the relationship between abnormal branches and association branches in the ventilation network, determine methods to improve the airflow volume of abnormal branches, and combine the regulation of the ventilator operating frequency and the resistance of associated branches. The combined ventilation system in the Da Liu-ta coal mine serves as a simplified experimental model of ventilation network structure, for which we develop a monitoring system and operating software. We then verify the practicability of variable-frequency regulation and the ventilation resistance of the branches was adjusted to meet the VOD in experiments. To protect the frequency conversion or the ventilation resistance regulating process of the ventilation system in practice, the ventilation resistance of associated branches, ventilator frequency, and joint regulation are simulated by the automated ventilation system adjustment software. The experimental results demonstrate the feasibility and efficiency of the three methods, and theoretical guidance for adjusting the branch VOD in the complex ventilation system in the coal mine is provided.

2. Approaches and theoretical models of airflow volume adjustment

In the coal mining process, changes in the network structure of the ventilation system are planned. However, toxic gas emissions and other catastrophic accidents occurred randomly and suddenly, leading to VOD changes and even changes in the airflow direction. Given that VOD changes under different conditions, the regulation of branch resistance and ventilator frequency conversion adjustment were analyzed, and theoretical models of VOD were established. Methods of ventilation system stability testing and advanced simulation judgment technology were studied during the regulation process, and the stability of ventilation systems during adjustment were effectively guaranteed.

2.1. *Models for branch resistance adjustment*

In the models for branch ventilation resistance adjustment, branch selection is particularly important, so we must establish a mathematical model to calculate the best adjustment branch. This study uses the cellular automation (CA) model to select the branch. CA is a grid dynamics model whose time and space states are discrete; thus, spatial interactions and cause and effect relations are local (Adrialy et al., 2012; Meunier, 2016). Each cell on the grid takes a finite discrete state and follows the same action rules; local rules are determined through a synchronization update, so many cells are involved in the evolution of the dynamic system through simple interactions (Achtemeier et al., 2012; Kassogue et al., 2017).

Fig. 1 shows the simplified network structure of a local ventilation system in a mine. If the VOD of Branch No. 3 needs to be increased to 6 m^3/s, by analyzing the approved ventilation ability, personnel air demand, gas emission, wind speed, and other factors, the minimum VOD of each branch is a criterion for determining the effect of regulation. The VOD regulation model was established using the principle of CA, and local

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