Journal of Loss Prevention in the Process Industries 47 (2017) 104–109

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

A transient model for airflow stabilization induced by gas accumulations in a mine ventilation network

Aitao Zhou, Kai Wang*

School of Resource & Safety Engineering, State Key Laboratory of Coal Resources and Mine Safety, China University of Mining & Technology, Beijing 100083, China

ARTICLE INFO

Article history:
Received 30 May 2015
Received in revised form
3 October 2016
Accepted 20 February 2017
Available online 6 March 2017

Keywords:
Transient model
Airflow stabilization
Gas accumulation
Mine ventilation network

ABSTRACT

To analyze the airflow stabilization induced by gas accumulations in a mine ventilation network, a transient model for airflow caused by gas accumulations is presented. The Runge Kutta method is selected to solve this model. To quantify the average gas density in the transient model, a solution to the gas diffusion equation in airways is interpreted. The Crank-Nicholson difference method is applied to calculate the gas diffusion equation, and the chase method is selected to calculate the gas concentration distribution in airways. Furthermore, a coupled solution between the transient model and the gas diffusion equation is proposed, and a transient airflow ventilation network program for this coupled solution is developed. According to the simulations conducted in this work, it is concluded that the results agree well with the field test. Finally, it was found that gas accumulation in inclined airways can generate gas ventilation pressure, which can lead to airflow disorder.

1. Introduction

A ventilation system is an important component in underground mining systems (El-Nagdy, 2013; Nyaaba et al., 2014; Xu et al., 2016). It should provide sufficient air quantity to the underground mine workers, dilute methane and other contaminants (Kursunoglu and Onder, 2015; Wallace et al., 2015), maintain a suitable working environment and prevent accidents from happening. In the operational stage of mine ventilation, the ventilation system status cannot simply be kept constant (Perera et al., 2012; Rusiński et al., 2014). Generally, coal mine ventilation is an extremely complicated system. A large number of influencing factors can control or impact the behaviors of the system (Cheng and Yang, 2012; Kazakov et al., 2015); mine fires are a common impacting factor. Many researchers have dedicated themselves to studying the stabilization of a ventilation system in the event of an underground fire and have obtained quantitative control measurements for the stabilization of dynamic ventilation systems during mine fires (Luo et al., 2014; Song et al., 2014). In addition to mine fires, gas accumulations can also influence the stability of airflow in the mine ventilation network. For example, during an outburst, a considerable amount of methane is released from the pulverizing coal (Guo et al., 2016; Zhao et al., 2016), these gas outbursts generate gas ventilation pressure, which can cause a reversal of airflow in certain airways. In some airways of the coal mine, there is a lack in airflow velocity leading to methane accumulations in these airways. Furthermore, if these airways are inclined, airflow disorder easily occurs. The influence of gas ventilation pressure on airflow in a single airway has been investigated (Zhou and Wang, 2016). However, airflow stability induced by gas accumulations in mine ventilation networks has not been interpreted. This paper aims to present a transient model for airflow stabilization induced by gas accumulations in a mine ventilation network and seek a solution for the transient model.

2. The airflow transient model of a ventilation network

2.1. Establishing an airflow transient mathematical model for a mine ventilation network

A mining ventilation system is generally regarded as steady when there are no disturbances (Sasmito et al., 2013; Wang et al., 2015; Zapletal et al., 2014; Zhou and Wang, 2016). However, when the airflow mixes with methane, the airflow rate and velocity will change, and the system is therefore transient. For a unit volume moving with the airflow, the following differential momentum

* Corresponding author. School of Resource & Safety Engineering, China University of Mining & Technology (Beijing), Beijing 100083, China.
E-mail address: safety226@126.com (K. Wang).

http://dx.doi.org/10.1016/j.jlp.2017.02.014
0950-4230/

equation in a single airway can be used (zhou, 1988).

$$K_i\frac{dQ_i}{dt} = h_{F_i} - \frac{1}{2}\overline{\rho}_i\left(u_{i_2}^2 - u_{i_1}^2\right) + \overline{\rho}_i g[z_i(0) - z_i(L_i)] - [p_i(L_i) - p_i(0)] - R_i|Q_i|Q_i \quad (1)$$

The pressure drop along airway i can be represented as

$$\begin{aligned} H_i &= p_i(0) - p_i(L_i) \\ &= K_i\frac{dQ_i}{dt} + \frac{1}{2}\overline{\rho}_i\left(u_{i_2}^2 - u_{i_1}^2\right) - \overline{\rho}_i g[z_i(0) - z_i(L_i)] + R_i|Q_i|Q_i - h_{F_i} \end{aligned} \quad (2)$$

If the areas of the different sections in the airway are constant, then $v_{i_2} = v_{i_1}$ and Equation (2) can be simplified to

$$H_i = p_i(0) - p_i(L_i) = K_i\frac{dQ_i}{dt} - \overline{\rho}_i g[z_i(0) - z_i(L_i)] + R_i|Q_i|Q_i - h_{F_i} \quad (3)$$

The mesh equation is given by:

$$\sum_{i=1}^{n} c_{ji}H_i = 0 \quad (4)$$

In Equation (3), let $h_{M_i} = \overline{\rho}_i g[z_i(0) - z_i(L_i)]$ and substitute Equation (3) into Equation (4), to obtain the final form:

$$\sum_{i=1}^{m} c_{ji}K_i\frac{dQ_i}{dt} = \sum_{i=1}^{m} c_{ji}\left(h_{F_i} + h_{M_i} - R_iQ_i|Q_i|\right) \quad (5)$$

where$K_i = \overline{\rho}_i l_i/A_i$, $C = [c_{ji}]$ is the fundamental-mesh matrix, $j = 1, 2, \cdots, b$, $b = m - n + 1$. If $c_{ij} = 1$, branch i is contained in mesh j and has the same direction. If $c_{ij} = -1$, branch i is contained in mesh j and the has opposite direction. If $c_{ij} = 0$, branch i is not contained in mesh j.

Equation (5) is the model for a mesh in a ventilation network.

Although the airflow density can be changed due to the density different between methane and air, the mixed airflow is incompressible and this airflow meets the continuity equations at the vertices, therefore:

$$\sum_{i=1}^{m} b_{ji}Q_i = 0 (j = 1, 2, \cdots, n) \quad (6)$$

In this equation, $B = [b_{ji}]$ is the incidence matrix. If $b_{ji} = 1$, the airway i is incident at junction j and is directed away from junction j. *If* $b_{ji} = -1$, the airway i is incident at junction j and is directed toward junction j. If $b_{ji} = 0$, the airway i is not incident at junction j.

According to the network theory, airflow rates in secondary airways can be evaluated from airflow rates in primary airways. Consequently,

$$Q_i = \sum_{k=1}^{b} c_{ik}q_k (i = 1, 2, ..., m) \quad (7)$$

where q_k is the airflow rate in a primary airway which is in mesh k. If the secondary airway i is contained in mesh k and has same direction, then $c_{ik} = 1$. If the secondary airway i is contained in mesh k and has opposite direction, then $c_{ik} = -1$. If the secondary airway i is not contained in mesh k, then $c_{ik} = 0$.

$b = m - n + 1$; The final mathematical model of the ventilation network under transient state conditions is given by combining Equation (5), Equation (6) and Equation (7), as follows:

$$\sum_{i=1}^{m}\left[c_{ji}K_i\left(\sum_{k=1}^{b} c_{ik}\frac{dq_k}{dt}\right)\right] = \sum_{i=1}^{m} c_{ji}\left(h_{F_i} + h_{M_i} - R_i\left|\sum_{k=1}^{b} c_{ik}q_k\right|\sum_{k=1}^{b} c_{ik}q_k\right) \quad (8)$$

2.2. The solution to the transient state airflow mathematical model

In Equation (8), R_i is a known constant; h_{F_i}, h_{M_i} are functions of time and airflow rate, respectively, and $q_k (k = 1, 2, \cdots, b)$ are unknown variables that are also functions of time. Equation (8) is difficult to solve directly, therefore, some simplifications are made.

1) To simplify Equation (8),

Let

$$a_{jk} = \sum_{i=1}^{m} c_{ji}K_i\sum_{k=1}^{b} c_{ik} (j, k = 1, 2, \cdots, b)$$

$$D_j = \sum_{i=1}^{m} c_{ji}\left(h_{F_i} + h_{M_i} - R_i\left|\sum_{k=1}^{b} c_{ik}q_k\right|\sum_{k=1}^{b} c_{ik}q_k\right) (j = 1, 2, \cdots, b) \quad (9)$$

To conveniently represent the solution, the variables are represented in matrix form as $A = [a_{jk}]$, $C = [c_{ji}]$, $C^T = [c_{ik}]$,$D = (D_1, D_2, \cdots D_b)^T$,$q = [q_1, q_2, \cdots, q_k]^T (k = 1, 2, \cdots, b)$, then $A = CKC^T$. When combined with Equation (9), Equation (8) is expressed in matrix form:

$$A\frac{dq}{dt} = D, \text{ that is } \frac{dq}{dt} = A^{-1}D \quad (10)$$

A number b of independent differential equations can be listed using Equation (10), therefore, this equation can be solved. The improved Euler algorithm (Runge Kutta method) meets solving requirements.

2) The solution to Equation (10)

Based on the finite difference theory, time is divided with the same time step τ, the corresponding time at the time t_n is $n\tau$. As shown in Equation (10), the partial derivative of the airflow rate is a function of time and the airflow rate of the primary airways, $q_k' = f_k(t, q_1, q_2, \cdots, q_b) (k = 1, 2, \cdots, b)$. According to the improved Euler algorithm,

$$\begin{cases} y_{n+1} = y_n + h(k_1 + k_2)/2 \\ k_1 = f(x_n, y_n) \\ k_2 = f(x_{n+1}, y_n + hk_1) \end{cases}$$

Then,

$$\begin{cases} q_k^{n+1} = q_k^n + \tau(k_{k,1} + k_{k,2})/2 \\ k_{k,1} = f_k(t_n, q_1^n, q_2^n, \cdots, q_b^n) \\ k_{k,2} = f_k(t_{n+1}, q_1^n + \tau k_{k,1}, q_2^n + \tau k_{k,1}, \cdots, q_b^n + \tau k_{k,1}) \end{cases} \quad (11)$$

In Equation (11), q_k^n represents the primary airway airflow rate at t_n. Because $f_k(t, q_1, q_2, \cdots, q_b)(k = 1, 2, \cdots, b)$ is a function of time and primary airways airflow rate, the airflow rate in the secondary airways needs to be converted to time and airway rate in the primary airways. As shown in Equation (10), fan pressure h_{F_i} and gas ventilation pressure h_{M_i} are also included in this equation. h_{F_i} can