Improvement of a mine fire simulation program — incorporation of smoke rollback into MFIRE 3.0

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Abstract

Smoke rollback is a dangerous threat to miners and firefighters in an underground mine fire. The ability to predict smoke rollback can greatly improve the chances for safe miner evacuation and mine fire control and firefighting. A modified semi-empirical equation based on large-scale experiments conducted by the National Institute for Occupational Safety and Health (NIOSH) was developed to quantify smoke rollback during an underground mine fire. The equation was incorporated into a mine fire simulation program (MFIRE 3.0) to allow the user to predict the occurrence of smoke rollback and calculate the smoke rollback distance. This article describes the development of the equation and compares the experimental results with those predicted by MFIRE 3.0. The results indicate that the improved MFIRE 3.0 is capable of determining smoke rollback in a fire entry, not only to provide early warning for smoke rollback but also to verify the effectiveness of smoke rollback control efforts.

Introduction

Smoke rollback, also called back-layering or smoke reversal, has received extensive attention from researchers investigating smoke control techniques.[1–5] Smoke rollback occurs in tunnels when the buoyancy force generated by a fire overcomes the inertial forces of

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ventilation to cause smoke migration upwind along the roof counter to the positive ventilation. Smoke rollback can be a dangerous and potentially fatal threat to miners and firefighters in an underground mine fire, preventing firefighters from getting close enough to fight a fire effectively in an underground mine entry. It can also bring flame from the fire back onto the firefighters. In addition, the heat from the rolling smoke from a fire occurring in a return airway may destroy stoppings used to separate intake and return airways. Subsequently, the smoke and products of combustion (POC) can contaminate the intake fresh air and be brought to the active faces where miners are working or evacuating.[6] Keeping an evacuation and rescue path free of smoke and hot gases is always the top priority during an underground fire rescue and evacuation. The ability to track the route of smoke spread and predict the occurrence of smoke rollback in an underground fire can greatly improve the chances for safe miner evacuation and mine fire control and firefighting.

Previous researchers[1,3,7] determined that smoke rollback is dependent on the tunnel dimension, the fire intensity, and the air velocity. In contrast to a road tunnel fire, an underground mine fire occurs in a more complex ventilation network where the interaction between the airflow and the fire makes the fire development and smoke spread much more complicated. A mine fire simulation program such as MFIRE is the best choice to represent the complicated interaction between the fire and the airflow in an underground mine fire. However, no existing fire simulation program has the ability to consider smoke rollback within such a ventilation network. Previous research on smoke rollback characterization during an underground mine fire was conducted by Zhou.[8] The results led to a semi-empirical equation based on large-scale experiments in a coal mine entry that were used to quantify the smoke rollback during an underground mine fire.

MFIRE is an underground mine fire simulation program originally developed in 1960s by the former U.S. Bureau of Mines (USBM) to predict the spread of fumes and other POC in a multilevel mine network.[9] Since then, several versions, including MFIRE 1.27, 1.29, 1.30, 2.0, 2.10, and 2.20, were produced. The most recent version, MIFRE 3.0, will be released by the National Institute for Occupational Safety and Health (NIOSH) in 2011. MFIRE 3.0 replaced the outdated FORTRAN programming language of MFIRE 2.20 with an object-oriented C++ approach, and split MFIRE into a user interface front end and an MFIRE class library back end. MFIRE was redesigned to allow third-party developers to obtain data directly from the back end (via common memory) rather than having to read data from the MFIRE ASCII format output. Some other improvements to MFIRE 2.20 were also made in MFIRE 3.0, including increasing the maximum size of the mine network, adding the ability to input and output data in both imperial and metric units, and the convenience of discrete event simulation. However, the upgrade from MFIRE 2.20 to 3.0 did not involve any improvements to fire and ventilation models. This article details the development and incorporation of a smoke rollback model, including the effect of airway slope, into the MFIRE 3.0 mine fire simulation program.

Three stages of smoke rollback

The development of smoke rollback in a mine entry or tunnel occurs in three distinct stages, as depicted in Figure 1(a) a critical velocity stage, Figure 1(b) a partial smoke rollback stage, and Figure 1(c) a complete smoke rollback stage.

The critical velocity stage is the period of time just before smoke rollback occurs. At this stage, the smoke forms a back layer at the same position as the upwind side of the fire source,

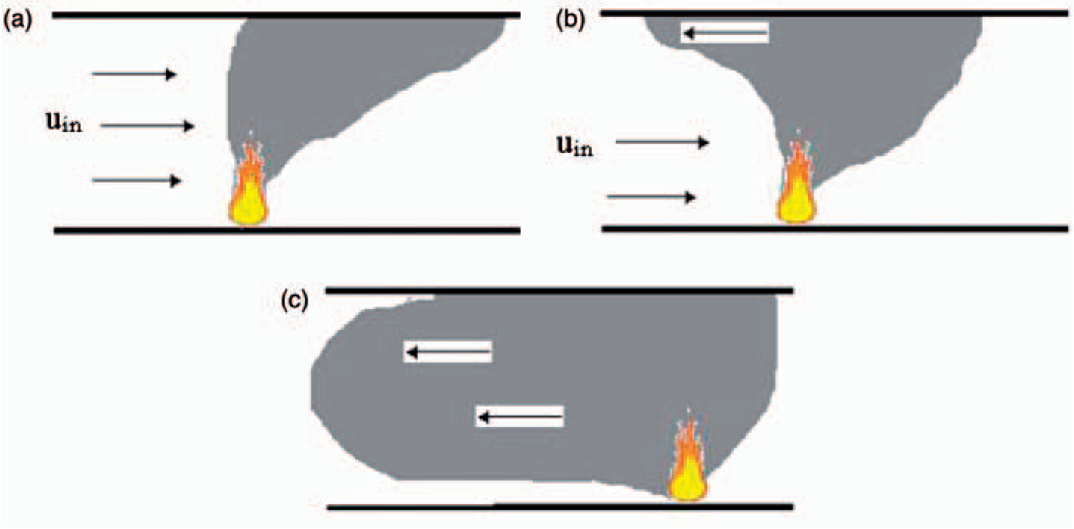

Figure 1. Schematic of the three stages of smoke rollback

shown in Figure 1(a). The critical ventilation velocity, u_{in}, is the minimum airflow velocity preventing the smoke from rolling back. The critical velocity has become one of the prime criteria used in the design of tunnel ventilation systems. Several researchers[3,7,10–12] have used the critical air velocity to predict the occurrence of smoke rollback. More details about the critical velocity will be described later in this article.

As the fire grows in thermal intensity, the inertial force of the intake airflow is overcome by the fire-generated buoyancy forces, and smoke begins to migrate along the airway roof counter to the intake airflow direction. At this time, two directions of flow co-exist in the airway, with the lower layer of fresh air maintaining its forward direction and the upper layer of hot smoke rolling back, as shown in Figure 1(b). This scenario is defined as the partial smoke rollback stage.

If the fire grows to sufficient intensity, it is possible for the airway to completely fill with hot smoke, causing total airflow reversal, as shown in Figure 1(c). This is known as the complete smoke rollback or smoke reversal. Complete smoke reversal rarely happens in road tunnel fires because the pressure differential between the two ends of the tunnel, which are both open to the atmosphere, is insignificant. However, it can and has occurred during underground mine fires because an underground mine fire exists not in a single airway but in a ventilation network with many branches, junctions, various controls, and fans. Throttling and natural draft changes generated by fires in underground mines can cause changes in the quantity of ventilating air currents, which can result in a reversal of the airflow direction. Similar changes can occur in neighboring connected airways as well as in the fire entry.[13]

MFIRE is capable of identifying complete airflow or smoke reversal.[14,15] However, partial smoke rollback is a three-dimensional problem beyond the scope of a unidirectional mine network program such as MFIRE. Compared with MFIRE, computational fluid dynamic (CFD) methods can simulate smoke reversal scenarios based on a 2- or 3-dimensional analysis. Although CFD methods have contributed to mine fire research, the limitations of CFD methods are also significant. CFD models can represent only a few entries at one time due to the current limitation in computer memory and processor speed. Thus, it is not possible to use a CFD model to simulate the propagation of a fire and the spread of contaminants on the scale of an entire mine. A CFD application to simulate smoke movement can provide detailed information only in a limited number of entries that have been isolated from a complete ventilation system.[6] As a result, from the viewpoint of the whole mine ventilation network, MFIRE cannot be totally replaced with a CFD model.

The prediction of smoke and contaminant spread during an underground mine fire is an important component for emergency planning. Accurate information about the early stage of smoke rollback is critical for the firefighting and miner evacuation planning. In an actual fire emergency, an early warning message of smoke rollback would be invaluable. Many unidirectional, semi-empirical equations have been created to identify smoke rollback in a tunnel or a single underground mine entry.[1,3,7,10,11] Those equations can be employed by programs such as MFIRE to predict the occurrence of the smoke rollback in an underground mine fire.

Critical velocity

Edwards et al. conducted diesel fuel fire experiments in the NIOSH Safety Research Coal Mine (SRCM) to determine the critical air velocity for preventing smoke rollback.[7] This was the first time that experiments to investigate smoke rollback were conducted in a real-sized mine entry (2.1 m high by 2.9 m wide [6.8 ft high by 10 ft wide]). The results showed a dependence of the dimensionless critical velocity (V_c^*) upon the dimensionless heat release rate ($\dot{q}^*$) to the one-third power:

$$V_c^* = 0.92\dot{q}^{*0.3} \tag{1}$$

where V_c^* and $\dot{q}^*$are defined by Equations (2) and (3), respectively:

$$V_c^* = \frac{V_c}{\sqrt{g\overline{H}}} \tag{2}$$

$$\dot{q}^* = \frac{\dot{q}}{\rho_0 T_0 C_p g^{1/2} \overline{H}^{5/2}} \tag{3}$$

The hydraulic tunnel height $\overline{H}$ in Equations (2) and (3) is defined as the ratio of 4 times the cross-sectional area to the tunnel perimeter. Prior to research by Edwards et al.,[7] Oka and Atkinson[1] and Wu and Bakar[3] also derived smoke rollback identification equations based on small-scale tunnel experiments using dimensionless analysis. The following general expressions were reported for the critical velocity in the Oka and Atkinson model, where $V_{\max}^*$ is 0.35:

$$V_c^* = \begin{cases} V_{\max}^*(0.12)^{-1/3}(\dot{q}^*)^{1/3} & \textit{where} \quad \dot{q}^* \le 0.12 \\ V_{\max}^* & \textit{where} \quad \dot{q}^* > 0.12 \end{cases} \tag{4}$$

From Equation (4), for a dimensionless heat release rate (HRR), $\dot{q}^* \le 0.12$, the critical velocity varies as the one-third power of the HRR, while the critical velocity is independent of HRR when $\dot{q}^* > 0.12$. Wu and Bakar[3] obtained a similar conclusion with their small-scale tests. They also improved the critical velocity equation by replacing the tunnel height H with the hydraulic tunnel height $\overline{H}$. In their equation, for a $V_{\max}^*$of 0.4, $\dot{q}^*$ becomes independent of the fire intensity at an HRR of 0.20.

The above equations are semi-empirical and based on experimental data collected by their developers. Some parameters, such as the critical dimensionless HRR, at which the critical velocity becomes independent of fire intensity, are dependent on the test conditions—0.12 in Oka and Atkinson's[1] equation and 0.20 in Wu and Bakar's[3] equation. Equation (1) from Edwards et al.[7] seems best adapted to the MFIRE improvement because it is based on the experiments conducted in a real-size, rectangular mine entry with actual wall roughness, while the other experiments were all conducted using scaled models with smooth walls. All the above factors are believed to have influence on smoke rollback.

In the context of the above, an important difference between Equations (1) and (4) and that of Wu and Bakar[3] is also noted. The latter two equations have two regimes of variation of critical velocity versus the heat released from fire. At low heat release rates, the critical velocity varies as the one-third power of the HRR; however, at higher heat release rates, the critical velocity becomes independent of fire HRR. Equation (1) shows only one regime of variation of critical velocity versus fire HRR. Zhou[8] has shown that the fire intensity in the experiment of Edwards et al.[7] is not large enough to demonstrate the independent relationship between critical velocity and fire intensity. Zhou expanded Equation (1) from one regime to two regimes based on the conclusions of Oka and Atkinson[1] and Wu and Bakar.[3] The modified Equation (1) is shown as Equation (5):

$$V_c^* = \begin{cases} V_{\max}^*(\dot{q}_{critical}^*)^{\ 0.3}(\dot{q}^*)^{0.3} & where \quad \dot{q}^* \le \dot{q}_{critical}^* \\ V_{\max}^* & where \quad \dot{q}^* > \dot{q}_{critical}^* \end{cases} \tag{5}$$

Where

$$V_{\max}^*(\dot{q}_{critical}^*)^{\ 0.3} = 0.92.$$

Implementation of smoke rollback identification

Identification equation

Substituting Equations (2) and (3) into Equation (5) yields the following expression:

$$V_c = \begin{cases} 0.92\dfrac{g^{7/20}}{\bar{H}^{1/4}}\left(\dfrac{\dot{q}}{{}_0T_0C_p}\right.^{0.3} & as \quad \dot{q}^* \le \dot{q}_{critical}^* \\ 0.92(g\bar{H})^{1/2}(\dot{q}_{critical}^*)^{0.3} & as \quad \dot{q}^* > \dot{q}_{critical}^* \end{cases} \tag{6}$$

Equation (6) is used by Zhou to calculate the critical velocity for an airway in an underground mine fire. One limitation of Equation (6) is that it fails to consider the effect of entry slope on the critical velocity, since it was developed based on the experiments with no entry slope.[7] Sloping entries are very common in underground mines, especially in metal or non-metal mines. The critical velocity in a mine entry with a downhill slope is greater than in the corresponding horizontal entry, while it will be less in a mine entry with an uphill slope. To address this issue, Atkinson and Wu[16] recommended a slope correction factor derived from experimental results for the downhill slope entry. The correction factor can be expressed as: $\alpha = 1 + 0.014\theta$, where θ is the entry slope in degrees. Equation (7) can thus be obtained after adding the correction factor into Equation (6):

$$V_c = \begin{cases} 0.92\dfrac{g^{7/20}}{\bar{H}^{1/4}} \quad \dfrac{\dot{q}}{{}_0 T_0 C_p} \quad {}^{0.3}[1 + 0.014\theta] & as \quad \dot{q}^* \leq \dot{q}^*_{critical} \\ 0.92(g\bar{H})^{1/2}(\dot{q}^*_{critical})^{0.3}[1 + 0.014\theta] & as \quad \dot{q}^* > \dot{q}^*_{critical} \end{cases} \tag{7}$$

Equation (7) is employed in MFIRE 3.0 to identify smoke rollback in an airway.

Determination of smoke rollback length

The extent of smoke rollback along the roof into the oncoming fresh air is also dependent on the ventilation velocity, airway dimensions, and fire intensity (HRR). Although the instability of the smoke reversal makes it difficult to define with great certainty the extent of smoke reversal for different ventilation velocities, a reduction of the data with dimensionless variables makes the trend more apparent in the Edwards et al. method.[7] For the smoke reversal length Lr, achieved for different ventilation velocities V_{in} and the HRR,$\dot{q}$, a pair of dimensionless variables, X and Y, can be defined as:

$$X = \dot{q}/(AV^3_{in} \quad {}_0) \tag{8}$$

$$Y = \frac{gL_r}{C_p(T_f \quad T_0)} \tag{9}$$

where T_{f} is average temperature of the fire-site gases in degrees K. Regression analysis showed that X and Y satisfy the following simple relationship with $R^2 = 0.68$:[7]

$$Y = 0.0238\ln(X) \quad 0.0479 \tag{10}$$

Substituting Equations (8) and (9) into the above relationship yields the smoke rollback length, L_r:

$$L_r = \left[0.0238\ln \quad \frac{\dot{q}(t)}{AV^3_{in} \quad {}_0} \qquad 0.0479\right]\frac{C_p(T_f \quad T_0)}{g} \tag{11}$$

Incorporation of smoke rollback identification into MFIRE 3.0

During an underground mine fire, the thermal disturbance generated by the fire can have a significant effect on airflow and temperature in each airway. This effect is, in turn, dependent on the HRR of the fire. This transient process in ventilation under the influence of fire can be represented by MFIRE. MFIRE is built on a ventilation network analysis technique and considers the development of mine fires, heat/mass transfer between the airflow and its surroundings, processes of thermal energy conversion into mechanical energy in an underground mining system, and transient state ventilation simulation techniques.[14] An interval-oriented simulation technique, which updates its data records at a pre-specified time interval, was adopted in MFIRE.[15] At each time interval, with the aid of a heat transfer model, the temperature and airflow in each airway can be obtained in the transient state simulation of MFIRE. Next, the other essential parameters of ventilation and fire can be calculated directly or indirectly with the known input data and the calculated airflows and temperatures in each time interval within a user-specified time span. With these calculations, MFIRE can trace the fire development, smoke spread, airflow distribution, and temperature distribution from one time interval to the next time interval.

As discussed above, all previous versions of MFIRE, including MFIRE 3.0, can simulate complete smoke reversal, but cannot simulate partial smoke rollback. In order to detect smoke rollback in a fire branch of the ventilation network, Equation (7) has been employed, and the corresponding computer code, written in C++, has been added to MFIRE 3.0. Generally, the critical velocity in a fire branch is determined by the geometry of the airway (expressed as the hydraulic height), HRR of the fire, and the slope of the airway. The hydraulic height is calculated from the perimeter and cross-sectional area of the airway, and the HRR of the fire can be obtained from MFIRE fire models, including the fixed heat input fire, oxygen-rich fire, and fuel-rich fire. The determination of the airway slope is calculated from the elevations of the starting and ending junctions and the length of the airway. The dimensionless HRR,$\dot{q}^*$, and the dimensionless critical HRR, $\dot{q}^*_{critical}$, have to be determined before applying Equation (7). Equation (5) can be used to calculate the dimensionless HRR. The dimensionless critical HRR was not determined in the Edwards et al.[7] experiments, but Oka and Atkinson[1] and Wu and Bakar[3] obtained values of 0.12 and 0.2, respectively. In the new MFIRE program, 0.12 is used as the default, but the program allows users to specify their own value.

At the end of each time interval, the airflow rate for each airway will be obtained from the MFIRE transient simulation. It is a simple matter to calculate the actual velocity of the fire branch with the known cross-sectional area. The main program then calls the function for calculating the critical velocity and compares the actual velocity to the critical velocity. If the actual velocity is lower than the critical velocity, the incoming airflow in the fire branch fails to prevent the smoke from rolling back. If the actual velocity is greater than the critical velocity, there is no smoke rollback. Besides the identification of smoke rollback, the program also calculates the length of the smoke rollback based on Equation (10). It should be also noted that the occurrence of smoke in an airway of a mine ventilation network can cause a resistance increase in the airway and subsequently impact the airflow. In this article, the impact of the partial smoke rollback on the airway resistance change is not considered because of its small contribution to the total airflow.

Case study

The mathematical model of smoke rollback described in this article is based on experimental studies conducted in a single entry without considering the influence of the adjacent connecting entries. Experiments in a ventilation network are required to validate the incorporation of this smoke rollback model into MFIRE. Edwards et al.[17] conducted four diesel-fuel-fire experiments in the NIOSH SRCM to study smoke rollback in a diagonal airway within a simplified ventilation network. Among all the experiments, Experiment No. 1 was selected to evaluate the identification of smoke rollback using the model described in this article.

Experiment No. 1 was conducted using the air course configuration shown in Figure 2. The entry heights were approximately 2 m (6.6 ft). B-Butt had an average width of 3 m (9.8 ft), whereas 11-Room and F-Butt were approximately 4- and 4.5-m (13 and 15 ft)

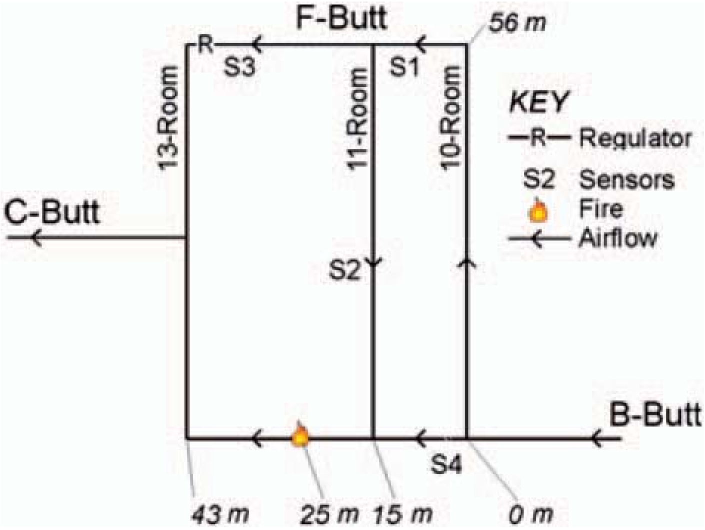

Figure 2. Schematic of the mine section for Experiment No. 1.[17]

wide, respectively. The mine exhaust fan established airflow in the mine from B-Butt to F-Butt and G-Butt through connecting rooms under normal ventilation condition. A diesel fuel fire with the heat release rate of 520 kW was started in B-Butt, 8 m (26 ft) downwind from 11-Room. Visual observations during the experiment indicated well-mixed smoke over the 10-Room cross section, and a thick roof layer of smoke was observed entering 11-Room from B-Butt. This indicates that smoke rollback occurred in the experiment. If there was no smoke rollback, the smoke should flow along the airflow to the C-Butt without contaminating 10-Room and 11-Room. The observations explain that the smoke flowed against the airflow from B-Butt to 10-Room.

Initially, MFIRE 3.0 was used to model Experiment No. 1. The network model is shown in Figure 3. The resistances of the branches range from 0.0107 (0.0958) to 0.2614 (2.34) $N \cdot s^2/m^8$ (10 ^{10} $in.min^2/ft^6$). A fire with a heat release rate of 522 kW (29,686 Btu/min) is specified at Branch No. 7. The computational results from MFIRE 3.0 showed that the airflow in Branch No. 5 reversed after the fire is added to Branch No. 7, due to the resistance that the fire added to Branch No. 7. The smoke generated by the fire flows downwind of the fire in Branch No. 7, into Branch No. 8, and finally flows out from Branch No. 10. This scenario indicates that Branches No. 2, 4, and 5 are clear of smoke. However, the experiment showed smoke contamination in these three branches. This simulation result would alert firefighters or rescuers that these branches are safe to enter when in reality these branches have smoke.

When the same case is simulated using the MFIRE program with the addition of the smoke rollback model, the output indicates that smoke rollback occurs. The smoke rollback occurs in Branch No. 7 after the fire is fully developed with a critical air velocity of 0.88 m/s. It was determined in the previous discussion that the critical velocity is determined by the fire intensity and the entry dimension. Because the fire intensity of the fixed heat fire source specified in the example and the entry dimension is constant, the critical velocity in the example remains constant.

It should be noted that a time-dependent fire source will result in a time-dependent critical velocity. In this case, the simulation indicates that the air velocity in Branch No. 7 was 0.68 m/s initially and then dropped to 0.29 m/s after 10 min. Thus, the airflow in

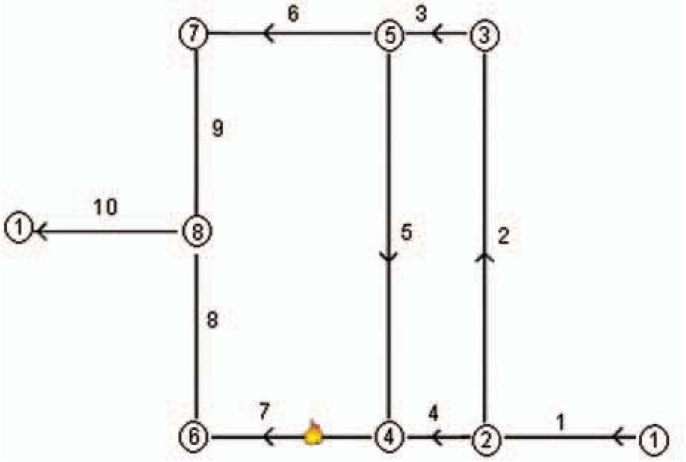

Figure 3. Ventilation network of Experiment No. 1.[17]

Branch No. 7 is not sufficient to stop the smoke rollback. In the simulation, the smoke reaches Node No. 4 after 3.5 min and then flows into Branch No. 5. The smoke also rolls back upwind to Node No. 2 and then enters Branch No. 2. The simulation results from the MFIRE with the smoke rollback model are consistent with the observations noted in Experiment No. 1.[17] This case study shows that the addition of Equations (7) and (11) to model smoke rollback has made MFIRE 3.0 capable of recognizing partial smoke rollback and the smoke rollback distance and its threat consequence.

Summary and conclusions

Smoke rollback is a dangerous and potentially fatal threat to evacuating miners and firefighters in an underground mine fire. It is of practical importance to know if an evacuation path is free of smoke in an underground mine fire emergency. The mine fire simulation program MFIRE is capable of tracking the smoke spread route in a ventilation network with consideration of the interaction between fire and ventilation. However, the non-dimensional MFIRE program is only able to simulate complete smoke reversal, with only one direction of flow, in an airway. The simulation of partial smoke rollback with the hot smoke layer flowing in the direction opposite to the ventilation stream is beyond the scope of previous MFIRE versions, including MFIRE 2.20 and MFIRE 3.0.

Several semi-empirical equations for identifying smoke rollback in a road tunnel or a single mine entry have been developed by other researchers. It was shown that the critical velocity, which is a criterion to recognize smoke rollback, varies as about one-third power of fire intensity at low HRR and is independent of fire intensity at higher HRR. Edwards et al.[7] developed an equation to identify smoke rollback in an underground coal mine fire after expanding it from one regime to two regimes and taking into consideration the effect of entry slope. Comparing the Edwards et al. equation[7] to the equations of the other researchers[1,3] shows that their equation is carried out based on a real-size mine entry with actual wall roughness while the other experiments are all conducted in scale-model with smooth walls. Secondly, the rectangular entry, common in US coal mines, is used in the Edwards et al.[7] experiments whereas the tunnels in the other experiments are arch types – the typical shape of a road tunnel. All the above factors are believed to have influence on smoke rollback.

Based on this comparison, the Edwards et al. equation[7] was incorporated into the new upgraded MFIRE 3.0 to identify the smoke rollback. The incorporation of these smoke rollback equations into MFIRE 3.0 makes it possible to recognize partial smoke rollback and the smoke rollback distance. An example based on an experiment in the NIOSH SRCM using the improved MFIRE model achieved good agreement between the predictions of the model and the experimental results.

Nomenclature

A = cross-sectional area of tunnel, m^2
C_p = specific heat of air at constant pressure, J/(kg,k)
g = acceleration due to gravity, m/s^2
$\bar{H}$ = hydraulic height of tunnel, m
L_r = length of smoke rollback, m
$\dot{q}$ = heat release rate, kW
$\dot{q}^*$ = dimensionless heat release rate
T_0 = temperature of the approach air, K
T_f = average temperature of the fire-site gases, K
V = velocity of the approach air, m/s
V_a = airflow velocity, m/s
$V^*_{\max}$ = dimensionless maximum airflow velocity
V_c = critical velocity of smoke rollback, m/s
V^*_c = dimensionless critical velocity
θ = entry slope in degrees

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