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Tenability analysis for improvement of firefighters' performance in a methane fire event at a coal mine working face

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Abstract

Due to the high rate of methane ignitions at active continuous miner working faces in underground coal mines, this location has been the focus of many researchers, as well as safety initiatives. Multiple ignitions occur annually in US mines, and outcomes vary widely based on the magnitude of the ignition and the subsequent damage to ventilation controls or development of active fire. Depending on the magnitude of the explosion or fire, auxiliary ventilation controls, such as exhausting line curtain or tubing may be damaged or completely removed, affecting the ventilation into the area. Investigation of a typical dead end continuous miner working face with exhausting ventilation was undertaken to explore firefighting conditions post ignition. Regular mining crews are trained in the fighting of mine fires, while mine rescue or fire brigade teams may also be utilized for firefighting depending upon the conditions. The research in this article develops an approach to analyze the tenable limits in a fire event in an underground coal mine for barefaced miners, mine rescue teams, and fire brigade teams in order to improve safety and training of personnel trained to fight fires. A detailed computational fluid dynamics analysis was conducted to investigate temperature, visibility, radiation, and concentration of combustion products based on different damage assumptions following an ignition at the continuous miner working face. The source of the combustion products analysis and the exposure effects were considered to assess the potential for harm to mine personnel, mine rescue teams, or fire brigades during a firefighting operation, taking into account their training and personal protective equipment during the 5- and 15-min exposure. This study has shown that if the exhausting line curtain was destroyed, the situation would not be tenable for barefaced personnel. The findings were utilized to recommend

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the tenable limits for barefaced miners, mine rescue team, and fire brigade teams during the 15-min exposure to the methane fire at a continuous miner working face. The outcome of this research, applied to training, will result in the more efficient evacuation, as well as safe and effective firefighting under certain conditions.

Keywords

Tenability analysis, computational fluid dynamics, barefaced miners, fire brigade teams, mine rescue teams, coal mine fires

Introduction

Tenability for fire situations has historically been considered for a number of occupied structures, to determine if conditions will allow for the escape of barefaced occupants and if conditions are tenable for trained firefighters to engage in firefighting or search and rescue. Tenability studies commonly consider heat effects, visibility, geometric considerations, air velocity, noise level, and toxicity during a limited time in tunnel fire events.[1–10] A unified treatment of the threats to incapacitation from exposure to fire effluent was presented in ISO 13571:2012,[11] and it is a consensus of experts, with the purpose of providing a standard approach to fire hazard calculations.

Safe escape for mining personnel is one of the most critical issues during a mine fire. It is important to note that approaching, fighting, and extinguishing a fire immediately can improve the safety since gassy coal mines can approach explosive limits, particularly when ventilation systems are negatively impacted. Tenability has been less formally studied and defined for the case of fires in underground coal mines in the United States where atmospheric and regulatory considerations are substantially different than for typical surface structures. In addition, while US municipal or public emergency workers may respond to surface installations at underground mines during an accident, they are not expected to enter a mine due to unique hazards in this environment. However, a systematic approach to tenability for personnel fighting underground coal mine fires could lead to improved safety and more efficient response.

Generally, there are three groups of people that could be expected to respond to fires in underground coal mines: barefaced mine personnel, fire brigade teams, and mine rescue teams. All underground coal miners in the United States are trained in firefighting, and operators are required to provide firefighting equipment including rock dust, fire hose and waterlines, and fire extinguishers, in addition to regulated automatic fire suppression systems at key locations.[12] Miners attempting to escape a mine with an active fire are encouraged to don self-contained self-rescuers (SCSRs) as soon as they suspect the atmosphere is compromised; however, most SCSRs commonly used in mines are not approved for firefighting. Therefore, for regular mine personnel, tenability for firefighting is considered for barefaced miners while tenability for escape would be considered for miners under standard escape SCSRs.[13] Fire brigade teams and mine rescue teams have similar equipment as surface firefighters, including fire-resistant clothing and rebreathers. Fire brigade teams tend to have training that is more specialized for fire-related emergencies while mine rescue teams are trained more broadly in mine emergency response. US law requires that mine personnel are trained in firefighting, suitable firefighting materials are available, and fire and evacuation drills are regularly held.[12] Mine personnel performing their regular jobs are expected to have

SCSRs, hard hats, safety glasses, boots with metatarsal protection, hearing protection, lights, and gloves; select personnel will also have a hand-held gas detectors (oxygen (O_2), methane (CH_4), and carbon monoxide (CO)). Furthermore, every mine shall have available a group of miners specifically trained in mine rescue and firefighting.[12] These teams must be able to deploy to the mine site within 1 h[13] and would be likely to have self-contained breathing apparatus (SCBA) appropriate for fire, light-duty fire-resistant clothing, and heavy-duty turnout gear, as well as access to ventilation materials and firefighting materials. Their training in search and rescue and firefighting is more extensive than that of other mine personnel.

This work only examines (1) barefaced mine personnel approaching a newly discovered fire and (2) mine rescue or fire brigade personnel under oxygen (i.e. SCBA) approaching a fire. Surface firefighting and rescue personnel (e.g. municipal or private) are usually available only for transport and treatment of victims as they are brought out of a US mine, because hazards associated with fire in underground mines are particularly specialized. Tenability criteria are often set at incapacitation for an average person. In this research study, more conservative criteria were utilized, since it was assumed that the firefighters must travel out of the mine without assistance. Mine fire response varies tremendously and is complicated by the underground coal mine environment. Small fires are typically extinguished quickly by barefaced personnel. Large and involved fires would seem to call for immediate evacuation of barefaced personnel (and the donning of SCSRs); however, in the underground coal mine environment, the risk of a catastrophic methane-dust explosion during an escape is considerable, and the deployment of mine rescue teams and fire brigades can be time-consuming. The decision to attempt an escape is difficult given that an explosive atmosphere could be developing and that escape routes can be several miles long. Crews must make such decisions within minutes of fire discovery. Furthermore, while there is literature devoted to various measures that impact tenability,[14] there are few examples that take a comprehensive approach to tenability. The literature that does exist is largely outside of the US context and provides broad approaches without a methodology for determining tenability.[15]

This work aims to investigate a scenario in which mine personnel are faced with a methane-fed mine fire and a face ventilation system that is compromised to varying degrees, examining tenability for barefaced personnel and fire brigades or mine rescue team members approaching the fire. The determination of the refuge chamber location was not investigated in this study, although other researchers have considered the factors such as speed of travel for miners in limited visibility wearing SCSRs,[16] as well as oxygen consumption under varying conditions[17] in investigating SCSR performance, optimal caching of SCSRs, and where to provide refuge chambers.

Precise numerical analysis of fire scenarios can improve safety and decision-making for all personnel faced with fire underground. In this study, five computational fluid dynamics (CFD) scenarios were simulated to analyze the tenability for personnel in a methane fire event in the continuous miner (CM) working face of an underground coal CM section. This work details preliminary investigation into the effects of different parameters such as heat and temperature, visibility, smoke layer depth, radiation and convection, and toxicity on tenable limits. For the purposes of this investigation, it is assumed that a face ignition has resulted in a face fire during mining production. The computational fluid dynamics software Fire Dynamics Simulator (FDS) Version 6.0 was utilized to predict the conditions that develop due to a 200-kW fire at the CM working face following a methane ignition with different levels of curtain damage. For a small ignition magnitude assumption, the ventilation curtain was not dislodged from its location so the curtain was 3 m far from the face, approximately the distance prescribed by US regulation (scenario 1). For increasingly powerful ignitions, it was assumed that the curtain was dislodged 6, 15, and 21 m, from the face in scenarios 2, 3, and 4, respectively. Finally, in scenario 5, the entire curtain was assumed to have been damaged. The tenability criteria were analyzed for 5- and 15-min exposure. The outcomes of this research were utilized to recommend the tenable limits for barefaced miners, fire brigade, and mine rescue teams in a 200-kW methane fire event at a CM working face. Ultimately, the developed methodology can be used for determination of tenable limits for barefaced miners, mine rescue, and fire brigade teams under different fire events situations and conditions.

Computational domain and design consideration

In this study, five different scenarios according to different assumed pre-ignition magnitudes were considered for tenability analysis in a methane fire event at a CM working face. All utilized parameters in the computational domain for five scenarios were the same except the length of the ventilation curtain. In scenario 1, no damage to the curtain was assumed so the curtain was 3 m far from the face. For the partially dislodged curtain, it was assumed that the curtain was damaged—essentially removed—6, 15, and 21 m from the face for scenarios 2, 3, and 4, respectively. In scenario 5, the whole curtain was removed from the computational domain as shown in Figure 1. The focus of the research in this article is to develop an approach to analyze the tenable limits in a methane fire event a coal CM working face for barefaced miners, fire brigades, and mine rescue teams. The CM working face is a hazardous operating region in the mine due to the potential for high levels of methane gas and coal dust during the mining process. Due to this gas release, frictional ignitions pose a considerable risk at the active working face in underground coal mines. The ignitions are initiated by methane conflagrations that may be gas fed or ignite the coal face. According to non-fatal fire reports of the Mine Safety and Health Administration (MSHA), active working faces are one of the most common locations where non-fatal injuries occur.[18] Therefore, the CM working face was selected for tenability analysis based on various degrees of assumed damage to an exhausting ventilation curtain. This study is based on a previous study[19] with the same geometry examining smoke layer depth, fresh air height, and interface height in a fire incident under different fire scenarios. Due to the difficulty in measuring the fuel mass loss in a real case scenario, the simulated 200-kW methane fire at the CM working face was based on the flame height and physical size of the fire which it was reported in 2000 MSHA mine fire accident reports[18] and was explained elaborately in Haghighat et al.[19] In this study, it was assumed that the ignited methane was on a coal surface that was 1-m long and 1-m wide. The airway and curtain were simulated according to the mine map as shown in Figure 1(a), number 8 entry, with exhausting line curtain set to the right side. The width and height of the entries were 6 and 1.8 m, respectively. The length of the entry (CM area) was set at 15 m. The schematic view and the dimension of the CM working face are shown in Figure 1. And, also the damage to the curtain can also be seen for each scenario in Figure 1(b). Based on the standard practice in underground mines, the CM was backed up to supported roof and de-energized as shown in Figure 1(b).

The thickness of the coal on the wall assumed to be 0.2 m. The thermal and the physical characteristics of Pittsburgh bituminous coal[20] were considered for the characteristics of the

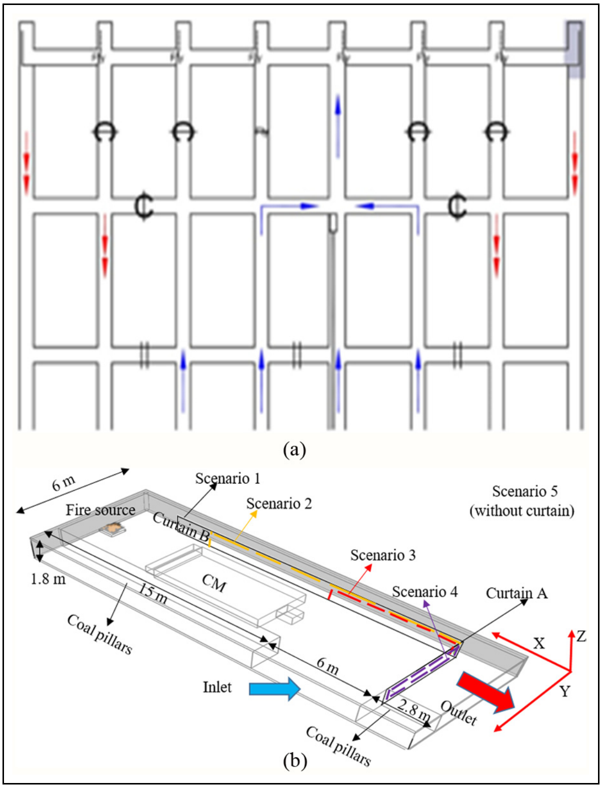

Figure 1. Selected CM working face with detailed specifications: (a) schematic view of CM working faces with detail in shaded in the upper right and (b) computational domain, dimensions, and the objects for all scenarios.

walls in all simulations. Emissivity of the coal was set to 0.96. The thermal and the physical properties of the steel for the CM were set according to the previous research study.[19] The heat of combustion and soot yield for methane fire were considered as 55.5 MJ/kg and 0.1 kg/kg, respectively. In some research studies, it was indicated that CO yield for methane fire can be increased by about a factor of 30 from 6×10^{-3} (4–5 ppm concentration) to 1.5×10^{-1} as the nitrogen flow is increased to the extinction limit (14.9% oxygen); therefore, 0.1 was considered as the CO yield.[21,22] The detailed characteristic of the exhausting line curtain was considered in the simulation of the scenarios 1 to 4. In scenario 5, the exhausting line curtain was removed from the computational domain. The high-density polyethylene was considered for the curtain properties (greater than 0.95 g/cm^3). Values of 1300 kg/m^3, 0.5 W/(m K), and 1.9 kJ/(kg K) were set as the density, thermal conductivity, and specific heat of curtain, respectively. Due to the ceramic fiber textile and polyethylene outer layer of brattice, the heat of combustion for the curtain was set to 43,600 kJ/kg.[19,23,24]

The inlet volume flow rate was set at 6.61 m^3/s based on a partner mine volume flow rate in the United States and the outlet was set to open. The ambient air temperature, ambient air density, and air viscosity at ambient temperature were set at 20°C, 1.196 kg/m^3, and

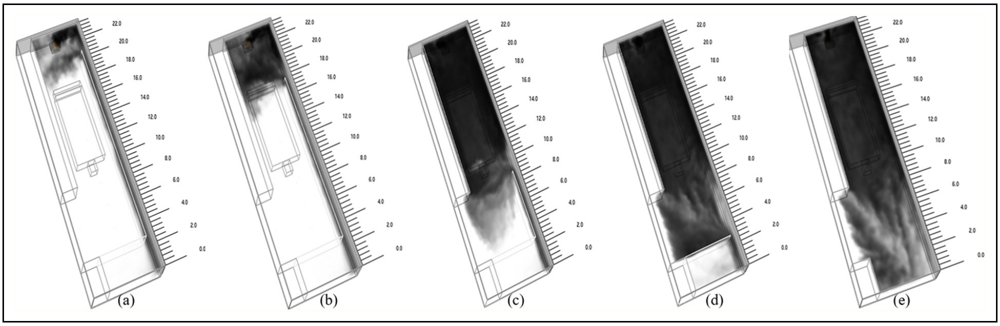

Figure 2. Isometric view of the smoke transport at t = 900 s in all scenarios: (a) scenario 1, (b) scenario 2, (c) scenario 3, (d) scenario 4, and (e) scenario 5.

1.79e−05 kg/m/s, respectively, in all simulations. Due to the critical effect of airflow to and from the fire volume on the controlling of the air replenishment for the fire and outflow of the hot, contaminated, and vitiated air to first responders, this parameter needs to be investigated, which was discussed in Haghighat et al.[19]

The T-squared approach[25] with the 0.00347 kW/s^2 as the fire growth coefficient was utilized for the growth of the methane fire at the face.[26] During the first 4 min of the methane fire event, the heat release rate (HRR) of the methane fire increased up to the maximum HRR (200 kW). Then, it remained constant until the end of the simulation. The whole simulation time was set to 900 s. The no-slip boundary condition was considered for the walls and the objects in the domain. The initial and boundary conditions were the same in all scenarios except the curtain length. The grid size was set at 5 cm for the numerical analysis of the 200-kW methane fire[19] as it was recommended that the reliable numerical results in FDS can be achieved with the usage of the grid size less than equal to $0.1D^*$ ($\leqslant 0.1D^*$) (where D* is representative of the characteristic length scale).[27–29] The turbulent viscosity in all simulations was considered as the Deardorff[30,31] turbulent viscosity with 0.1 as the Deardorff coefficient (C_v). The turbulent diffusivity was obtained using a 0.5 as the constant Schmidt number (Sc_t) (for mass diffusivity) and a 0.5 as the constant Prandtl number (Pr_t) (for thermal diffusivity). The default value (0.35) was considered as the radiative fraction (the fraction of energy released from the fire as thermal radiation) in this study. The mixing-controlled combustion[32] was considered as the combustion model in this study. All scenarios were simulated as shown in Figure 2 to demonstrate the effect of the intact and completely destroyed auxiliary ventilation system. The gray and black colors in Figure 2 represent the concentration of smoke at different parts of CM working face.

One of the most important issues in numerical computations is finding the appropriate level of grid resolution. This is a function of the flow conditions, type of solver, geometry, and other variables. One is often left to start with a grid resolution and then conduct a series of grid refinements to assess the effect of the grid resolution. Roache[33] explained a consistent manner for calculation of a grid convergence index to estimate the discretization error based on Richardson extrapolation (RE). This approach was used to estimate the discretization error in the CM face fire simulations. Three different mesh sizes as shown in Table 1 are considered in the Grid Convergence Index (GCI) calculation. The average temperature of smoke-laden layer at X = 18.8 m (in front of CM (the selected location for tenability analysis)) in scenario 5 (worst case scenario) is the key variable of interest in this study. A value

Table 1. Discretization error for average temperature of smoke-laden layer at X = 18.8 m in scenario 5 at 900 s.

Characteristics	$\emptyset$ = average temperature of smoke-laden layer
Fine mesh elements (N1)	3,379,200
Medium mesh elements (N2)	422,400
Coarse mesh elements (N3)	52,800
$\emptyset_1$ (°C)	76.0
$\emptyset_2$ (°C)	75.1
$\emptyset_3$ (°C)	70.7
GCI_{fine}[20]	0.4%

of 1.25 as the safety factor[34] for comparison among three meshes was utilized in this analysis. The grid refinement factor was set to 2. The GCI_{coarse}[33] was not investigated since the focus of this study was on the error quantification for the finer meshes. The considered grid sizes for fine, medium, and coarse meshes were 5, 10, and 20 cm, respectively.

As shown in Table 1, it is evident that the numerical uncertainty (estimated error) in the fine grid GCI for average temperature of the smoke-laden layer at $X = 18.8$ m in scenario 5 is calculated as 0.4%.

Tenability and the US coal mining context

In this study, five main parameters were considered to investigate tenability for barefaced miners, fire brigade, and mine rescue teams: visibility, temperature, smoke layer depth, radiation, and toxicity. These parameters have been extensively utilized for analysis of the tenable limits in the road tunnels.[1] In addition, it was assumed that the main mine ventilation system operates continuously.[12] The concentration of toxic species effects (e.g. CO and CO_2) for the fire brigade and mine rescue teams were not considered for tenability analysis since the team members carry SCBA. They are designed to provide oxygen for at least 4 h and are appropriate for firefighting. For barefaced mine personnel, the toxicity of CO and CO_2 are considered, as well as O_2 deficiency. For both barefaced teams and teams under oxygen, explosibility should be considered in comprehensive tenability analysis. If personnel observe or expect combustion, the advance of people into an explosive atmosphere (e.g. 5%–15% methane in the presence of standard oxygen) is not tenable because the risk of fatal injury is immediate and imminent. However, in this preliminary study, emissions of methane from the coal strata were not incorporated, so we did not consider explosibility.

Temperature and heat effects

Radiation from hot gases and areas and convection from hot gases are two main sources of heat exposure for mine personnel during firefighting in underground coal mines. It is noteworthy that the percentage of water vapor in the combustion products plays a key role on burning of the respiratory systems. The inhalation of the air, containing less than 10% water vapor, cannot influence on the burning of the respiratory system. Generally, the tenability limits for skin burns are lower than for burns to the respiratory tract. By inhalation of the saturated water vapor air with a temperature above 60°C (140°F), the respiratory tract thermal burns happen.[1,2] Tenability for temperature during a fire event depends on the dose of heat over a period of time. A longer exposure to a lower temperature or heat flux is usually more tolerable than a short exposure to a high radiant heat flux or temperature.[2] In NFPA® 502, equation (1) was recommended for calculation of time of exposure to a certain amount of temperature

$$t_{exp} = (1.125\times 10^{7})T^{-3.4} \tag{1}$$

where t_{exp} is time of exposure to reach a fractional effective dose (FED) of 0.3 min; T is temperature (°C). For the calculation of the maximum exposure time without incapacitation in equation (1), some crucial factors (e.g. evacuees were lightly clothed, zero radiant heat flux, the constant exposure temperature, and the FED is ≤ 0.3) were considered.[2]

The tenability limit for the exposure of skin to radiant heat is approximately 2.5 kW/m^2.[35] It is likely that people can tolerate exposure at this level for 30 min or longer.[1] Our simulation also considers convected heat from hot gases which are the dominant source of heat transfer during a fire incident in underground coal mines. Pain and skin burns can occur at air temperatures above 120°C.[2] The rate of heat transfer from hot air to the skin via convention depends on different parameters including the rate of ventilation, humidity, air temperature, and clothing.[36,37]

Visibility

Smoke can limit visibility to the degree that it is difficult for personnel to approach a fire, and if they do approach, it may still be nearly impossible to assess the magnitude and involvement.[19] An atmosphere will usually reach the tenability limits for visibility well before the limits for gas concentrations, temperature, and radiation.[38]

Visibility and the processes affecting it are crucial not only for the safety of self-evacuation of people in the mine but also for fire brigade and mine rescue teams since the infrared cameras are not utilized in rescue missions in underground mines. Visibility has an immense impact on walking speed during evacuation period or fighting the fire. Jin and Yamada[39] proposed a relationship between the visibility and walking speed. Frantzich and Nilsson proposed an equation (equation (2)) for calculation of walking speed

$$u_w = -0.1423 \cdot C_s + 1.177 \tag{2}$$

where C_s and u_w are extinction coefficient and walking speed, respectively. If visibility (V_s) is used as the independent parameter, equation (3) can be utilized for calculation of walking speed[38]

$$u_w = 0.5678 \cdot V_s + 0.3033 \tag{3}$$

Numerous experiments have been carried out by different scientists on the determination of walking speed during fire incidents. However, based on the Swedish building code, the basic unhindered walking speed was recommended at 1.5 m/s. For children or people with disabilities, the walking speed was recommended to be set to 0.7 m/s.[38]

Consistent with the data of several different experiments which were plotted in tunnel fire dynamics book in terms of walking speed as a function of visibility, it was concluded that the walking speed range was changed from 0.2 to 1.5 m/s when the visibility was in the range of

0–10 m.[40,41] Therefore, in this study, the mean velocity (0.85 m/s) was selected as the walking speed for evacuation time calculation and speed. However, it is noteworthy that the walking speed could be changed for injured evacuees, elder mine personnel, or however for mine rescue, fire brigade teams. In addition, the evacuation path, the slope of the airways, and the mine height can influence the travel speed. Hence, a comprehensive experiment is needed for precise calculation of walking speed in underground mines. However, based on previous study on the travel speed of the miners in heavy smoke situation, it was evident that the average travel speed was 0.4 m/s, which the average travel speed increased to 0.97 m/s in clean air situation.[42]

FDS utilizes an approach to calculate visibility at an arbitrary 30-m distance based on the soot yield of combustible materials.[43] For purposes of this work, tenable visibility limits were set to 10 m; however, this is one of the most subjective criteria, and depending on circumstances, firefighters may proceed in more limited visibility.

Toxicity

In this study, the O_2 deficiency and the effects of CO and CO_2 for barefaced personnel were considered to investigate the toxicity in order to recommend the tenable limits during a methane fire event in an underground coal mine. Carbon monoxide decreases the possibilities for the blood to take up, carry, and deliver oxygen to the tissues and combines with the hemoglobin in the blood to form carboxyhemoglobin (COHb).[4] CO produces negative health effects including neurological effects, such as cognitive impairment, dizziness, and unconsciousness,[44] and can be fatal at high concentrations. The detrimental effects of different levels of COHb on human health are summarized in Nelson[45] and Varon et al.[46]

Carbon dioxide affects the time to incapacitation in two different ways. At low concentrations, CO_2 acts as a stimulus, increasing the breathing rate, and influencing the uptake of other asphyxiant gases (e.g. CO), and, at concentrations greater than 5%, CO_2 can become an asphyxiate,[38] with risk of unconsciousness within a few minutes when the concentration of CO_2 is above 7%.[6] In this study, all numerical calculation in terms of toxicity was carried out at $z = 1.5$ m as the height for barefaced miners, as it expected they would make every effort to stay below the smoke layer.

Calculation of exposure levels and tenability criteria

When examining both heat and toxicity, the best indicator of exposure is dosage over time. In addition, the stimulus effect of CO_2 can increase uptake of CO, so the additive and multiplicative effects of these gases should be considered. FED is an indicator of dosage and can be calculated for exposure to heat or gaseous species. The FED concept was first proposed by Kaplan and Hartzell.[47] FED is calculated based on a 15-min exposure time, following the method proposed by Purser[5] and displayed in equation (4)

$$FED_{tot} = (FED_{CO} + FED_{CN} + FED_{NOx} + FLD_{irr}) \times HV_{CO2} + FED_{O2} \tag{4}$$

For this study, only CO_2, O_2, and CO were considered. Given the relatively short simulation time, standard oxygen was maintained, so oxygen deficiency was not considered, and the equation is simplified to equation (5)

$$FED_{tot} = (FED_{CO}) \times HV_{CO_2} + FED_{O_2} \quad (5)$$

In equation (5), FED_{CO}, HV_{CO_2}, and FED_{O_2} can be calculated according to equations (6)–(8)[5]

$$FED_{CO} = \int_0^t \frac{C_i}{(C \cdot t)_i} dt = \int_0^t 2.764 \times 10^{-5} (C_{CO}(t))^{1.036} dt \quad (6)$$

$$HV_{CO_2} = \frac{exp(0.1903 C_{CO_2}(t) + 2.0004)}{7.1} \quad (7)$$

$$FED_{O_2} = \int_0^t \frac{dt}{exp[8.13 - 0.54(20.9 - C_{O_2}(t))]} \quad (8)$$

where t is time in minutes, and C_{O_2} and C_{CO_2} are the O_2 and CO_2 concentrations in percent. C_{CO} is the CO concentration in ppm. The HV_{CO_2} is defined as the hyperventilation factor induced by carbon dioxide.[5]

While it is clear that FED gives a more comprehensive measure of health effects, providing better tenability criteria, it is not practical to calculate dosage in real time for miners in active fire scenarios. Table 2 summarizes criteria proposed by various groups and includes Short Term Exposure Limits (STEL), based on a 15-min dose, as well as ceiling (C) limits which should not be exceeded. These data are used to inform the proposed tenability criteria.

Results and discussion

Smoke layer depth, temperature, and visibility results

The fire smoke level is the main factor for a safe escape. Because it can influence visibility and increase risk of incapacitation. The interface height and the fresh air height[32,48] were considered for investigation of smoke layer depth at different parts of the CM area.

The mean temperature and the mean visibility, the mean interface height, and the mean fresh air height along the height of the entry at the different cross sections for scenarios 1–5 were calculated. The mean interface height and fresh air height along the X axis at $t = 900$ s at different parts of the entry for all scenarios are shown in Figure 3.

Table 2. Criteria for exposure to various products and effects of fire.

Standard	CO (ppm)	CO_2 (%)	O_2 (%)	Heat	Temperature
ACGIH	25 TWA	3.0 STEL	19.5	–	–
NIOSH	200 C	3.0 STEL	19.5	–	–
OSHA	50 TWA	3.0 STEL	19.5	–	–
MSHA (coal)	400 STEL	3.0 STEL	19.5	–	–
MSHA (M/NM)	400 STEL	1.5 STEL	19.5	–	–
NFPA® 502	450 STEL		19.5	2.5	60

Source: MSHA;[18] NFPA;[2] OSHA[3].
STEL: Short Term Exposure Limit (15-min dose); C: ceiling limit; TWA: Time-Weighted Average.

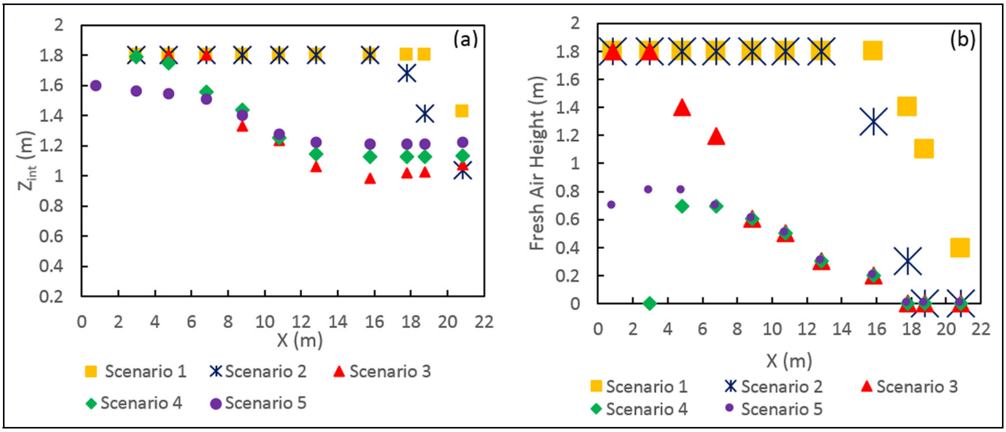

Figure 3. Average height of different layers along the *x* axis at 900 s: (a) average interface height and (b) average fresh air height.

Based on the simulation results, it was evident that as ventilation curtain damage increased, the smoke movement in the out by direction in the CM area of entry increased. In addition, by getting further from the fire source, the fresh air height and interface height increased. The upstream smoke movement from the mouth of the exhausting line curtain in scenarios 1, 2, and 3 were 2.5, 3.4, and 5.5 m, respectively. In spite of limited auxiliary ventilation in scenarios 4 and 5, some air reaches the fire source. However, in general, the smoke accumulated through the entire depth of the CM area. It is noteworthy that the thickness of the hot, smoke-laden layer close to the fire source increased when the curtain was dislodged partially or fully in the CM area as shown in Figure 3. All in all, we refer the readers to Haghighat et al.[19] for detailed interface height and fresh air height study based on different levels of damage to an exhausting line curtain in CM area. The average temperature for different layers along the height of tunnel was calculated as shown in Figure 4 to analyze the tenability criteria for barefaced miners, mine rescue teams, and fire brigade teams. The average temperature for two different layers at both sides of the interface height along the *x* axis is illustrated in Figure 4.

The average cooler layer height is the average temperature of the layer from floor to the interface height (Figure 4(b)), and the average temperature of the smoke-laden layer is the average temperature of the layer from interface height to the ceiling. In Figure 4(a), it is evident that average temperature of the smoke-laden layer is close to that of the cooler lower layer temperature (20°C) for scenarios 1 to 4 at 4.5, 7.5, 16.5, and 20.3 m from the fire source. In addition, the average temperatures of the cool layer close to the fire source for scenarios 1 and 2 were only slightly higher when compared to scenarios 3, 4, and 5. Moreover, it was evident that by getting further from the fire source the smoke-laden layer temperature decreased. According to Figure 4(a), by decreasing the exhausting line curtain by about 3 m, the average temperature increased by about 23°C at $X = 20.8$ m. The average temperature of the smoke-laden layer in the CM area for scenarios 3, 4, and 5 were calculated almost the same as shown in Figure 4(a). This study has shown that the length of the curtain played a key role in the average temperature of the smoke-laden layer close to the fire source.

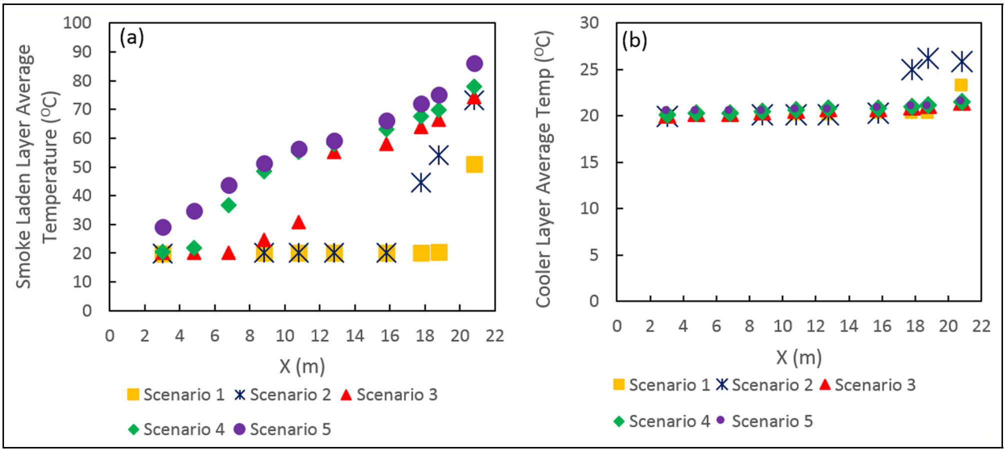

Figure 4. Average temperature of different layers along the *x* axis at 900 s: (a) smoke-laden layer temperature and (b) cooler layer temperature.

For the calculation of the visibility along the height of the tunnel at different cross section, the height of 1.5 m was considered since it was assumed that the barefaced miners, mine rescue, and fire brigade teams would try to stay below the smoke layer. The mean visibility at the height of 1.5 m at different cross sections of the tunnel in scenarios 1–5 was calculated as shown in Figure 5(a). Consistent with the data of Figure 5(a), it was evident that the mean visibility at different parts of the CM area at $z = 1.5$ m was less than 10 m in scenarios 3, 4, and 5. However, the mean visibility was more than 10 m in scenarios 1 and 2, when we get further from the fire source by about 4.5 and 7.5 m, respectively. In addition, a location (4.5 m away from the fire) was considered to investigate the mean visibility along the height of the tunnel at selected cross section as shown in Figure 5(b). The criterion for the selection of the location was based on the distance that both the barefaced personnel and mine rescue teams or fire brigades would approach. Each point on the visibility line graph (Figure 5(b)) represents the average visibility from the left rib to the right rib at $X = 18.8$ m (4.5 m away from the fire source) at the indicated height at 900 s for all scenarios. According to Figure 5(b), the 10-m visibility at that cross section was achieved at height of 1.8, 1.1, 1.1, 0.7, 0.9, and 1.1 m in scenarios 1, 2, 3, 4, and 5, respectively. Overall, the study of the mean visibility has shown that the length of the exhausting line curtain has had an immense impact on the visibility at different cross sections. Moreover, the effect of the ventilation curtain length on the mean visibility at different heights of the tunnel close to the fire source was consequential.

Toxicity results

In this study, the concentration of CO, CO_2, and O_2 at different sections of a CM working face during 900 s of methane fire were calculated to investigate the toxicity rate at the CM working face of an underground coal mine. The average personnel height should be considered for investigation of toxicity at associated location. Therefore, 1.5 m as the height for barefaced miners was selected, as it expected they would make every effort to stay below the smoke layer. The effect of the exhausting ventilation curtain length on an average mass

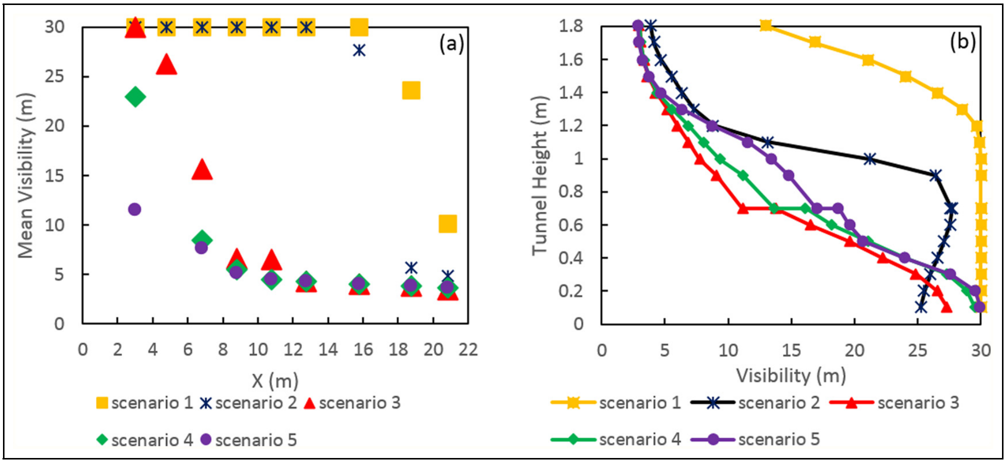

Figure 5. Mean visibility at 900 s: (a) along the length of the tunnel at z = 1.5 m and (b) along the height of the tunnel at *X* = 18.8 m.

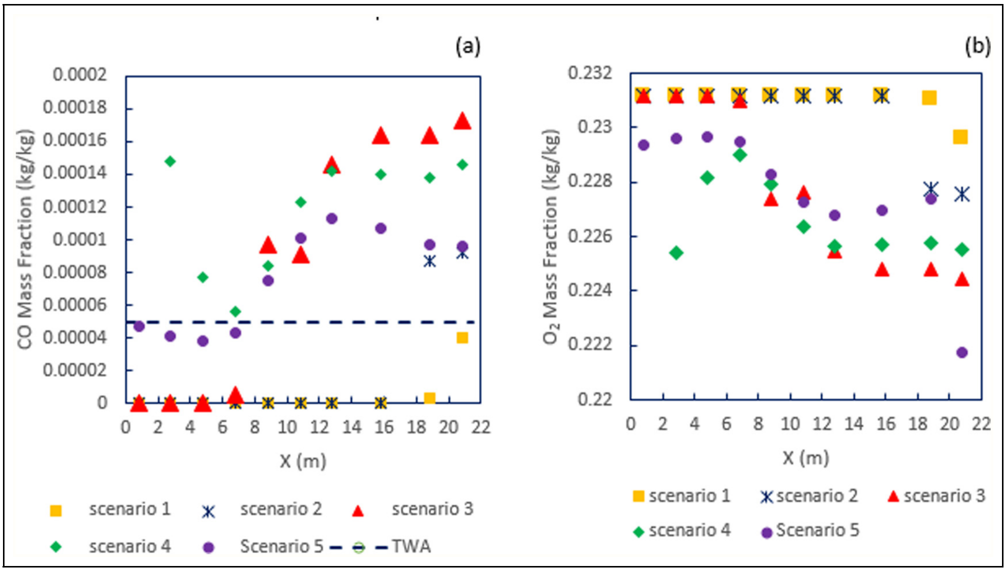

Figure 6. Average mass fraction along the length of the tunnel (*x* axis) at z = 1.5 m, *t* = 900 s: (a) average CO mass fraction and (b) average O_2 mass fraction.

fraction of CO and O_2 at 900 s at $z = 1.5$ m are shown in Figure 6(a) and (b), respectively. It is evident that the concentration of CO passed the TWA level while O_2 was maintained at more than 19.5% Threshold Limit Value (TLV) at all locations. Furthermore, the exhausting ventilation curtain substantially impacted the decrease of the CO concentration around the CM in scenarios 1 and 2. As can be seen in Figure 6(a), the CO concentration decreased when the distance from the fire source increased. However, in scenario 4, the CO

Table 3. Calculated results for all scenarios at X = 18.8 m, z = 1.5 m, and t = 900 s in CM working face.

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
CO concentration (ppm)	0	121	280	280	280
CO_2 concentration (%)	0.08	0.09	0.7	0.7	0.7
O_2 concentration (%)	23	22.6	22	22	22
Temperature at height 1.5 (°C)	23.7	54.2	95.3	95.3	95.3
Visibility (m)	25.8	5.5	1.3	1.3	1.3
Interface height (m)	1.8	1.2	1.12	1.12	1.12
Smoke-laden layer average temperature (°C)	20.5	54	84	84	84
Cool layer average temperature (°C)	20.5	26.2	21.4	21.4	21.4
Radiant heat flux (kW/m^2)	0.1	0.11	0.13	0.13	0.13

concentration increased at X = 2.8 m and 20.5 m from the fire source to 147 ppm. The reason lies in the absence of a ventilation curtain parallel to the long axis of the entry in scenario 4, which it contributed to the accumulation of the smoke in just adjacent to the cross-cut. Consistent with the data of CO_2 concentrations along the height of the tunnel at different cross sections, it was evident that the CO_2 concentrations in scenarios 1 and 2 (scenarios with exhausting line curtain in CM area) were less than the TWA level (0.5%) during 900 s while the concentration of CO_2 exceeded the TWA level when the ventilation curtain was removed from the CM area (scenarios 3, 4, and 5). The CO_2 concentration in scenarios 3, 4, and 5 were calculated by about 0.7% in CM area at X = 18.8 m.

A summary of the results for all five scenarios at X = 18.8 m (4.5 m away from the fire source) and z = 1.5 m (selected location for the tenability analysis) in the CM working face at t = 900 s is shown in Table 3.

Preliminary tenability recommendations

Average values for toxicity, temperature, and heat were calculated during five different periods of time after the initiation of a methane fire at a CM working face in all scenarios. We assume that both barefaced personnel and mine rescue teams or fire brigades would approach within 4.5 m of the fire (X = 18.8 m), so this location was selected as the area for investigation of tenable limits for mine personnel, fire brigade, and mine rescue teams during firefighting. Next, 1.5 m was selected as the height for barefaced miners, as it expected they would make every effort to stay below the smoke layer. Therefore, results for the concentrations of gases, fractional incapacitating doses, temperature, and visibility are investigated at that height. The least and the most damage to the curtain scenarios (scenario 1 and 5) results are shown in Table 4. Smoke behaved similarly at the CM area in scenarios 3, 4, and 5 since the ventilation curtain was dislodged from the CM area in these scenarios. Therefore, the tenability analysis is the same for the aforementioned scenarios. The simulation results indicate that the smokeless sections for scenarios 1 and 2 are at about 6 and 9 m from the fire source, respectively. Moreover, the visibility is more than 10 m at those sections when there is curtain at the CM working face. With the full removal of the ventilation curtain, the smoke accumulated through the entire depth of the entry and ventilation bypassed the region. After 4 min (when the HRR reached 200 kW), the whole CM area filled with smoke (scenarios 3, 4, and 5).

Table 4. Average concentration of toxic and physical hazards and fractional incapacitating dose for 5- and 15-min periods during methane fire at a CM working face in scenarios 1 and 5.

	Scenario 1		Scenario 5		Proposed tenability criteria (15-min exposure)*	
Time (min)	5	15	5	15	Barefaced mine personnel	Mine rescue/ fire brigade
CO concentration (ppm)	0	0	**270**	**280**	200 ppm	$<125,000$
CO_2 concentration (%)	0.07	0.08	**0.7**	**0.7**	<0.5	–
O_2 concentration (%)	23	23	22.1	22	>19.5	–
Fractional effective dose	–	0.0243	–	**1.447**	<1	–
Temperature at height 1.5 (°C)	23.7	23.7	**90.5**	**95.3**	<60	<100
Visibility (m)	23.4	25.8	**1.3**	**1.3**	>10	>10
Interface height (m)	1.8	1.8	1.18	1.12	–	–
Smoke-laden layer average temperature (°C)	20.2	20.5	**83**	**84**	<60	<100
Cool layer average temperature (°C)	20.2	20.5	21.1	21.4	<60	<100
Radiant heat flux (kW/m^2)	0.09	0.1	0.1	0.13	<2.5	<5.0

*Simulation results that exceed proposed criteria for barefaced personnel are bold.

The proposed tenability criteria for barefaced firefighters and mine rescue or fire brigade teams, along with the data from scenarios 1 and 5, at 5- and 15-min are shown in Table 4. The proposed tenability criteria are applicable for all studied scenarios. The initial condition of CM working face was assumed to be tenable without a methane fire. Tenability criteria were developed based on the various limits given in Tables 2 and 4. For barefaced miners approaching the fire, the most conservative limits were utilized for several reasons. First, there is some uncertainty associated with the application of FED (equations (4)–(8)) to individuals; and second, evacuation from a mine fire is complicated by long evacuation paths (on the order of miles) and the donning and changing of SCSRs. Miners experiencing CO intoxication can find their abilities to make critical decisions impaired, so a conservative ceiling value of 200 ppm for CO was utilized. There is speculation that impairment due to intoxication complicates evacuation and has contributed to fatal injuries in mine fires.

Since the focus of the research in this article is to develop an approach to analyze the tenable limits in a methane fire event a coal CM working face for barefaced miners, fire brigades, and mine rescue teams, the parameter sensitivity study was not considered in this study. A parameter sensitivity study should be performed, showing that any one scenario is not highly sensitive to the parameters chosen or providing reasonable error bars of tenability calculations based on reasonable error in parameter selection.

Tenability for barefaced miners

In scenario 5, incapacitation by heat was reached at 2 min 36 s when the temperature of the smoke-laden layer exceeds 60°C (140°F). Furthermore, the time to the tenability limit of 10 m for visibility was reached by 1 min 16 s. So, for scenario 5, it would not be tenable for barefaced mine personnel to approach and fight a 200-kW fire. Conservatively, the miners would be exposed to CO intoxication and they would certainly be exposed to unacceptable heat levels and compromised visibility. The FED is higher than 1, which also indicates untenable conditions for scenario 5. However, in scenario 1, various tenable limits, including FED, were not exceeded. Fire approach and firefighting under scenario 1, intact ventilation, is tenable for barefaced miners, at least up to 15 min. They also must assess the risk of explosion when deciding whether to fight a fire or evacuate, so evacuation is not without risk. In examining these scenarios for a fire of about 200 kW, it is clear that if the face ventilation has been destroyed (scenario 5), the situation is not tenable for barefaced personnel. First, they may be exposed to intoxicating levels of CO, and the subsequent disorientation could hamper later evacuation attempts. Next, the visibility is quite low, and the temperature near the fire is not tenable as it exceeds 60°C, and this personnel is not in turnout gear.

Tenability for mine rescue teams and fire brigades

The previous section details tenability for barefaced miners in standard work clothes. Tenability is entirely different for mine rescue or fire brigade teams in the same situation. There is no tenability limit in terms of gas toxicity since the teams carry breathing apparatus (SCBAs). Teams must be cautious of explosive atmospheres, particularly explosive levels of CO and methane; the lower limits are 12.5% and 5%, respectively, in the presence of standard oxygen. Mine rescue teams and fire brigades do not typically carry infrared cameras, but are prepared to work in lower visibility and often tether themselves together. Gas temperature and flame radiation were considered for investigation of tenable limits for rescue teams in underground mines, assuming that they are in standard fire turnout gear. Heat-related tenability limits for firefighters in turnout gear are reported as high as gas temperature ≤100°C (212°F) and radiation ≤5 kW/m^2;[1] however, these are probably not tolerable in a full 15-min dose.

The visibility limit of 10 m was reached at 1 min 16 s, and the visibility continued to decrease with time. Therefore, after 5 min, the rescue teams do not have enough visibility at a height of 1.5 m to fight the fire. Again, visibility is perhaps the most subjective tenability criteria, and near-zero visibility is not uncommon during firefighting. This is a criterion that teams may consider on the ground, possibly proceeding under low visibility under certain circumstances. Visibility can be substantially improved if teams install ventilation as they approach the fire, which is standard practice for teams traveling a mine during emergencies.

Ultimately, both scenarios are tenable with the exception of visibility for specially equipped mine rescue and fire brigade teams, at least up to 15 min. It is likely that such teams would be approaching the fire long after the 15-min mark, and the simulation should be expanded to consider up to at least 1 h.

Conclusion

Numerical fire simulation was utilized to investigate a specific set of scenarios in an active CM face, ventilated by exhausting line curtain. Tenability criteria were researched and proposed for approaching a mine fire in an active CM working face. This study illustrates that the status of ventilation controls has a substantial effect on tenability for personnel engaged in firefighting. This work applies to the training of mine personnel in responding to face fires: it is reasonable to miners that they can consider barefaced firefighting when ventilation controls are intact and they are actively monitoring the atmosphere, but evacuation or reventilation is necessary if ventilation controls are destroyed. This scenario is best left to mine rescue or fire brigade teams. These scenarios should be studied over a longer period of time than 15 min to further inform mine rescue and fire brigade approach.

Broadly, this study can inform further work in the ways miners are trained in firefighting and be utilized to further develop tenability criteria for various personnel in underground coal mines. First, we recognize that mine personnel is extensively trained in firefighting and have access to firefighting equipment, so their preparation differs from that of the average structure occupant on the surface. Fire simulation, in concert with reasonable tenability guidelines, can be used to train miners as to when approaching fire barefaced is appropriate and when evacuation is the best option. These simulations applied to training will result in more efficient evacuations (e.g. the decision to leave can be made quickly and with less delay), as well as safe and effective firefighting under certain situations. Also, it is clear that while US regulation provides for firefighting training and equipment for all mine personnel, provision of basic firefighting personal protective equipment (PPE) and a limited number of SCBAs could allow for immediate control of fires that could not otherwise be approached by barefaced personnel.

Finally, future work must account for explosibility by further examining combustion of methane and the effect of various strata emission levels. In addition, tenability criteria should be further examined and formalized for various mine fire scenarios, as this approach can lead to more effective decision-making for personnel faced with fire and supervisory personnel during emergencies, ultimately improving safety by mitigating fire early.

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