Process Safety and Environmental Protection 177 (2023) 617–634

Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.journals.elsevier.com/process-safety-and-environmental-protection

Underground mining fire hazards and the optimization of emergency evacuation strategies (EES): The issues, existing methodology and limitations, and way forward

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ARTICLE INFO

Keywords:
Underground mines fire hazards
Computational fluid dynamics
Emergency evacuation
Agent-based models
Smart evacuation

ABSTRACT

Underground mine fires are associated with thermal and non-thermal hazards. Thermal hazards are primarily characterized by the release of heat into the underground confined space. The non-thermal hazards are noxious gases primarily carbon monoxide produced from incomplete combustion which may be circulated to other parts of the sub-surface environments through the ventilation network. Consequently, it is paramount to understand the interaction of possible fire scenarios and the underground ventilation system due to the hazards fire poses in such environments to design an appropriate emergency evacuation plan. This work aims to present a comprehensive review of the status of underground mine fire studies, techniques for emergency evacuation planning, the merits and limitations of the existing methods, the current best practices, and the way forward to develop an integrated smart solution for improved safety practices in underground environments. In addition, this study further identifies critical factors based on experimental and numerical fire studies that could substantially improve fire safety and emergency preparedness in underground confined environments, thus optimizing the management of emergency evacuation plans in such environments.

1. Mine fire disasters and evacuation challenges

Mine fires have been a leading historical cause of mass fatalities in the mining industry (Stewart, 2021; Tang et al., 2021). They pose a serious threat to underground mine workers, and efforts to eliminate the potential of fires in a mining environment are still far from realization. Mine fires may occur from equipment leakages, tire fires, conveyor belt fires (Yuan and Smith, 2015), or oxidation and explosion in coal gobs (Xiang et al., 2021). Data from the literature show that about 177 fires occurred in the US mines between 2009 and 2018 (Tang et al., 2021). One of the most recent mine fire happened in September 2022 at a Utah mine. Although the fire caused no injuries, it however lasted for about a week (KSL.com, 2022). A report from the National Institute of Occupational Safety and Health (NIOSH) on mine disasters showed that fire accidents are the second most rampant mine accidents in terms of fatalities in all underground mines (including metals, non-metals, coal, and stone) in the US (NIOSH, 2021). Mine fire accidents are not restricted just to the US mines; similar concerns have also been reported in Australia and China (Hansen, 2018; Zhu et al., 2019). In Australia, for instance, a total of 128 fires were reported in underground hard-rock mines between 2008 and 2012 (Hansen, 2018). While in China, statistical analysis has shown that explosions and fires are the major cause of fatalities in underground coal mines (Zhu et al., 2019).

One of the major challenge miners faces during evacuation is caused by smoke roll-back. The event of smoke roll-back otherwise called back-layering, as depicted in Fig. 1, can pose a serious challenge to safe evacuation (Zhou, 2009). Back-layering occurs when smoke and hot combustion products that were created close to the tunnel ceiling flow against the ventilation stream due to fire-induced bouyancy flow. This circumstance arises when the airflow velocity is below the minimum (critical) velocity of airflow required to prevent smoke roll-back. The smoke roll-back could be catastrophic in underground mines because of its high toxicity, which might impair the miners while attempting self-escape (Fan et al., 2018; Lin and Chuah, 2008; Wu et al., 2018). Numerous studies have investigated smoke roll-back length and have developed methodologies to combat it. The studies have demonstrated that a minimum ventilation velocity is critical to designing safe tunnels and underground systems (Fernández-Alaiz, Castañón,

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https://doi.org/10.1016/j.psep.2023.07.012
Received 21 December 2022; Received in revised form 14 June 2023; Accepted 3 July 2023
Available online 5 July 2023
0957-5820/

Gómez-Fernández, and Bascompta, 2020; Hwang and Edwards, 2005; Ingason and Li, 2010a; Tsai et al., 2010).

Poor preparedness is another major challenge that could significantly impact a safe and timely evacuation mission from underground fires (Brnich et al., 2010; Chasko et al., 2005; Conti, 2005; Jinzhang and Fengxiao, 2022; Onifade, 2021; Queensland-Government, 2022; Singh et al., 2021). This may arise from human perspective preparedness such as the inability of miners to locate the emergency exit quickly, deploy appropriate PPEs, or due to poor stress management skills of the personnel. On the other hand, it may arise from delays in facility preparedness such as the readiness of the egress system which includes the escape shaft, ventilation door, etc., or the overall response capability of the mine operators. Previous research has shown that severe fatalities occurred in underground mines due to the inability of the miners to find a self-escape route quickly which could prolong the evacuation time. According to a study (Brnich et al., 2010), the findings indicated that over 80% of miners who lost their lives in a mine disaster survived the initial incidents but perished while trying to self-escape. It was observed that miners were not aware of the self-escape route and decided to make use of familiar but unsafe exit ways during a fire. A more recent survey conducted by another group of mine rescue services showed that more frequent preparation such as physical capacity tests, quarterly refresher tests, and training of miners about fire rescue skills could enhance mine rescue missions (Onifade et al., 2022). The complicated geometry and the limited numbers of evacuation routes, and the long-distance miners must navigate through to reach a safe zone are some other factors that could contribute to the complexity of any underground evacuation mission.

Therefore, it is imperative to prepare an emergency evacuation plan to prevent/minimize fatalities that may occur due to underground fires. Such techniques could enable miners self-escape during a fire as mine rescuers may sometimes be unable to evacuate miners who are trapped in refuge chambers (Halim and Brune, 2019). This can be achieved by developing an appropriate evacuation model using illeigent agent-based sysytem. Such evacuation models incorporate the capability of evaluating an emergency evacuation process by computing the risk factor and the chances of self-escape to the surface. Although many works have illustrated how this approach could be deployed in underground mines, the development of such practical and reliable self-escape models is still at its infancy. Conversely, several researchers have worked on the development of safe evacuation models for buildings and transport tunnels (Hu et al., 2014; Kuligowski, 2008; Mossberg et al., 2021; Shen, 2005; Yuan et al., 2009). They have demonstrated that developing an emergency plan before the occurence of an incident is crucial to a successful evacuation mission and disaster prevention.

This paper's goal is to present the status of experimental and numerical studies on underground fires to understand their hazards and give insight into ways to improve emergency evacuation planning. Fig. 2 shows the structural flow chart of this paper. Firstly, we present an overview of mine fire disasters and the major causes of underground fire hazards. Then, the methods for fire studies using laboratory and full-scale experiments are presented, followed by the discussion of the quantification of major fire characteristics which includes the heat release rate (HRR), flame characteristics, and smoke spread behavior. The experimental findings which provide inputs for fire simulation studies are further discussed in Section 5. The goal of experimental and numerical fire studies is to enable more elaborate quantification of fire risk for dynamic reconstruction and visualization of underground fire scenarios, thereby helping to improve safe emergency planning. Thus, in Section 6 we address the merits and shortcomings of the existing methodologies for emergency evacuation planning and propose a robust agent-based approach. This paper is valuable in helping researchers and the mining/underground construction industry to understand the onus of the available evacuation strategies and how they can be best applied to different underground fire hazard scenarios.

2. Mine fire experimental studies

Generally, experimental methods or numerical simulations are used for mine fire studies. Fire experiments could be conducted using laboratory models or reduced-scaled tunnels (Cheng et al., 2001; Ingason and Li, 2010a), or full-scale fire experiments performed in real underground mines/tunnels (Hansen, 2019; Hansen and Ingason, 2013a, 2013b).

2.1. Overview of mine fire studies

In the US, the 1951 Orient Mine Disaster, which claimed the lives of 119 miners, caused the Bureau of Mines to conduct in-depth research on the fire resistance of cables, hydraulic fluids, and conveyor belts in other to assess the fire risks (Smith and Thimons, 2009). The Bureau produced an acceptance standard for conveyor belts in US mines in 1955 as a result, marking a notable advancement in the field. With the successful creation of the MFIRE ventilation code in the 1970 s, mine fire research was furthered. By 1962, the Bureau of Mines had finished its first ventilation studies using the fluid network analyzer for contaminant dispersion. The NIOSH Lake Lynn Laboratory (LLL) started operations in 1980. By 1984, the facility had a fire gallery that enabled full-scale flammability testing of the mine conveyor belt. Mine fires study continued to experience tremendous growth in the 1990 s. The Bureau of Mines created a software program that could evaluate the danger of spontaneous combustion in underground mining operations (Smith and Thimons, 2009). Between 1995 to 1996, the Bureau of mines was closed, and some of its functions were transferred to NIOSH. By 2001, NIOSH and the Mine Safety and Health Administration (MSHA) began a collaboration to further understand the characteristics of mine fires to identify the capabilities as well as the limitations of the mine fire suppression technologies. Since then, NIOSH researchers and MSHA technical specialists have worked together on the science of mine fires, mine fire control, and suppression technology (Trevits et al., 2009).

2.2. Laboratory experiments

The key parameters that characterize fire experiment classification are the pool size and the tunnel size. The size of the pool affects how fire behaves and how quickly heat is released. Studies have shown that the heat release rate (HRR) is linearly related to the pool size (Marková et al., 2020). Even though there is no generally acceptable classification of fire pools based on their sizes and earlier classification of fire pools was based on whether the fire is radiatively or convectively dominated, some researchers have tried to categorize fire pools with respect to the pool diameter. For instance, fires in pools of diameter < 0.2 m are

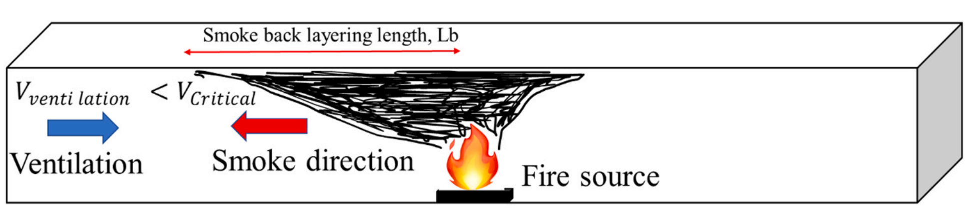

Fig. 1. Schematic representation of smoke back-layering.

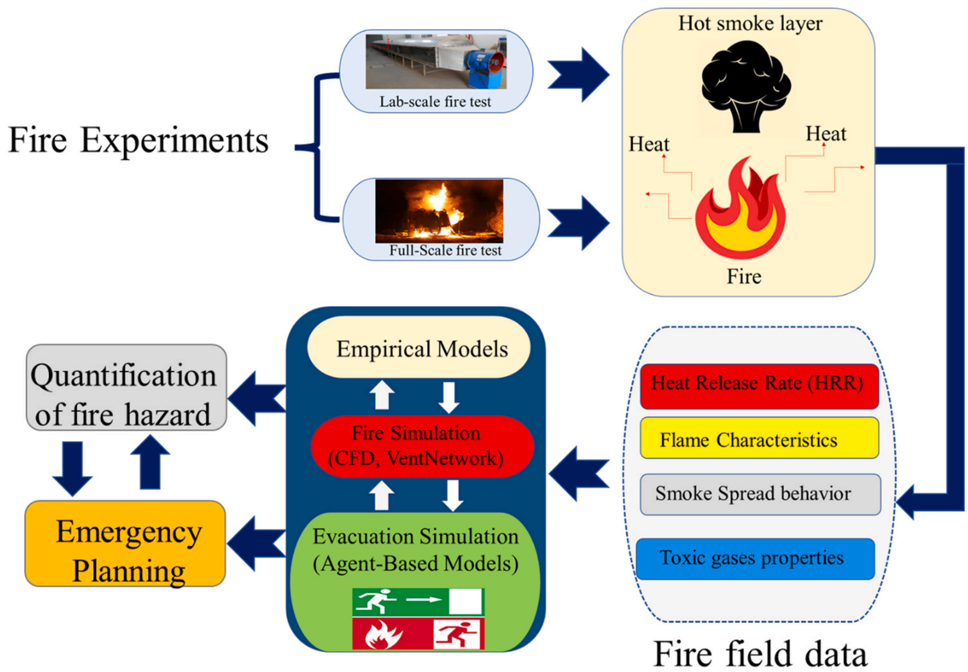

Fig. 2. Graphical abstract of this study.

generally classified as small pool fires while pool sizes of between 10.0 and 100.0 m are regarded as large pools for fire research (Steinhaus et al., 2007). Pool fires can be divided into three categories, according to Palacios et al.(Palacios et al., 2020): large-scale pools (D≥ 1.0 m), medium-scale pools (0.1 m ≤ D < 1.0 m), and small-scale pools (D < 0.1 m). Whereas, another study defined pool diameters larger than 0.2 m as large pool fires (Babrauskas, 1983). In a different study, pool areas are used in defining pool sizes, with 10.0 m^2, 25.0 m^2, and 50.0 m^2 considered as small, medium, and large pools respectively (R. O. R.O. Carvel et al., 2001; R. Carvel et al., 2001).

Laboratory fire experiments are generally conducted in reduced-scale model tunnels which are usually made of fireproof materials, and as such could be limited to small or medium size pool fires. Typical instrumentation of a laboratory fire experiment and thermocouple instrumentation for five measuring stations (S1-S5) separated 1.0 m apart is shown in Fig. 3. The setup consists of two gas monitors denoted as G, and two monitoring cameras upstream and downstream of the fire to capture the real-time evolution of the fire in the tunnel. Sometimes, fire experiments are conducted under different longitudinal ventilation conditions, while in other cases, they are conducted under free burn conditions. Stainless steel (Li et al., 2010) and transparent Promatect H board (Ingason and Li, 2010a) are the popular materials used for tunnel construction. The size of the tunnel generally ranges from a few meters to about 100.0 m depending on the available facilities and experimental design. For instance, a previous study (Li et al., 2010), examined back-layering length and critical ventilation velocity using a 12.0 m long model stainless steel tunnel while a 10.0 m long model tunnel built for a laboratory experiment was used to investigate HRR and other fire characteristics under differing ventilation conditions in another similar study (Ingason and Li, 2010a).

The Froude formulae is used to determine the corresponding value of the fire characteristics on a full-scale based on the results obtained from laboratory tests. Although these correlations have been widely used by many researchers, they are only theoretical calculations and still require a series of validation studies. Table 1 itemizes the scaling formulae used for determining the corresponding full-scale fire properties based on laboratory experiments. (In Table 1, L = length, Q = heat release rate, V = velocity, t = time, E = energy, M = mass, T = temperature while subscripts $_F$ and $_M$ denote full-scale values and model tunnel scale values respectively) (Chow et al., 2010; Ingason and Li, 2010b; Li et al., 2011; Oka and Atkinson, 1995).

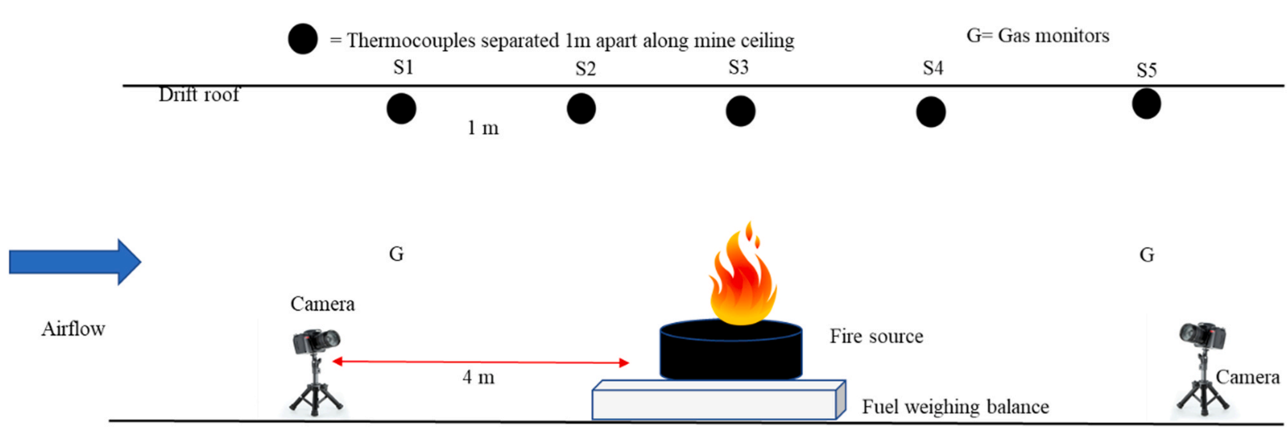

Fig. 3. Typical instrumentation of laboratory fire experiments.

Table 1
Scaling correlation of laboratory and full-scale fire parameters.

Parameter	Scaling correlation
Heat release rate (HRR), kW	$\dot{Q}_F = \dot{Q}_M \left(\frac{L_F}{L_M}\right)^{5/2}$
Velocity, m/s	$V_F = V_M \left(\frac{L_F}{L_M}\right)^{1/2}$
Time, s	$t_F = t_M \left(\frac{L_F}{L_M}\right)^{1/2}$
Energy, kJ	$E_F = E_M \left(\frac{L_F}{L_M}\right)^{3} \left(\frac{\Delta H_{c,M}}{\Delta H_{c,F}}\right)$
Mass, kg	$M_F = M_F \left(\frac{L_F}{L_M}\right)^{3}$
Temperature, k	$T_F = T_F$

2.3. *Full-scale fire experiments*

The experimental instrumentation for full-scale tests is analogous to the laboratory setup presented in Fig. 3. The major difference is that the experiments are conducted in the actual underground airways or tunnels (see Fig. 4). They involve conducting real fire experiments mostly by burning diesel, and gasoline pools, or sometimes burning abandoned/damaged machinery such as dozers or drilling machines in an underground mine. Experiments conducted in massive laboratories such as the NIOSH LLL that mimic real mining conditions could also be considered full-scale fire experiments. These kinds of tests are difficult to repeat due to their high expense and time requirements, yet they continue to be the most trustworthy method of validating current mine fire modeling software (Hansen, 2019; Hansen and Ingason, 2013a).

Previous researchers have established the importance of performing full-scale experiments to evaluate and analyze simulation results from computer models produced from computational fluid dynamics (CFD) and ventilation network analysis. In a scenario, a full-scale fire study was conducted to investigate the CO spread in an underground mine, and the results were compared to verify MFIRE capability (Zhou et al., 2018). In the study, the simulated CO concentration was compared to the measured data at three different locations in the NIOSH Safety Research Coal Mine (SRCM) laboratory, and findings from the study indicate that a full-scale experiment could help validate simulation models. Sometimes, conducting full-scale fire tests may be the only feasible solution because simulation tools such as CFD are only effective to model a portion of a mine and cannot accurately model complicated mine networks (Yuan et al., 2016).

Evaluation of fire characteristics and their effect on fire safety is also done using full-scale fire testing. In one investigation, a full-scale fire experiment that involved burning mining vehicles in an underground mine was carried out to examine how quickly various underground mining vehicles generate heat (Hansen, 2019; Hansen and Ingason, 2013a). The fire tests involved an underground wheel loader unit and a drill rig. The drilling rig reached its maximum HRR of 29.4 MW after 21.0 min of combustion, while the wheel loader reached its maximum HRR of 15.9 MW about 11.0 min after ignition (Hansen and Ingason, 2013a). The study is important because the information gathered can be used for estimating the overall heat release rate of mining trucks. It could also be used to generate HRR curves for specific mining vehicles. The findings from the study remain a major milestone in the history of mine fire studies as the study is one of the few attempts to investigate the fire dynamics of burning mining vehicles in the underground. Some of the other important mine fire experimental studies that have significantly contributed to our knowledge of mine fire dynamics are presented in Table 2.

Fig. 4. A picture of full-scale fire tests in the Missouri S&T experimental mine.

3. Influence of important parameters for underground mine fire hazards studies

3.1. *Impacts of ventilation*

Ventilation is a critical factor that influences fire dynamics in confined spaces and may cause significant changes to the fire evolution and product of combustion spread (Beard et al., 1999; Hansen, 2019). An earlier investigation to examine the effect of forced longitudinal ventilation on HRR for vehicle fires in tunnels using a Bayesian estimate affirmed this proposition. It was shown that a velocity of about 3.0 m/s may cause the fire size to increase by a factor of up to 5.0 if no mechanical ventilation is used for heavy goods vehicles (HGV) (R. R.O. Carvel et al., 2001; R. Carvel et al., 2001). In a similar vein, increasing ventilation for large pool fires in tunnels or mine airways may increase the heat release rate by up to 50.0% at a velocity of 10.0 m/s (R. R.O. Carvel et al., 2001; R. Carvel et al., 2001). Small pool fires, on the other hand, show a stark difference. For small pool fires, increasing the ventilation will tend to reduce the size of the fire, and this may be attributed to the fact that small pool fires are fundamentally fuel-controlled (Beard et al., 1999; R. R.O. Carvel et al., 2001; R. Carvel et al., 2001).

Generally, two major ventilation systems, namely the forcing and the exhausting are common in fire studies experiments. Although most laboratory investigations of fire behavior with longitudinal ventilation adopted the forcing ventilation technique (Beard et al., 1999; R. R.O. Carvel et al., 2001; R. Carvel et al., 2001; R. O. R.O. Carvel et al., 2001; R. Carvel et al., 2001), a few fire experiments used the exhausting ventilation system. Regardless of the ventilation system adopted, the goal is to prevent smoke back-layering by operating the fan to achieve air flows above the critical velocity (Beard et al., 1999; Kong et al., 2021; Tsai et al., 2010). Even though the primary aim of longitudinal ventilation is to help prevent smoke roll-back, experiments have shown that certain increases in the longitudinal ventilation will only cause the fire to burn faster and increase the fire growth rate (Beard et al., 1999). Most fire experiments in mines and tunnels are designed based on the configuration and already existing situation in the mines, and only a limited adjustment can be made to the mine layout, thereby restricting the choices of fan selection for experimental purposes.

3.2. *Back-layering length*

Smoke back-layering is a non-thermal hazard from mine fires (Khan et al., 2016), and the extent of the back-layering length is another critical parameter for underground space/tunnel fire safety design. Numerous studies have shown strong dependence between ventilation velocity and back-layering length. The critical velocity on one hand has been proven to be dependent on the fire size and applying appropriate longitudinal ventilation could help mitigate the effect of smoke roll-back. In one case study of smoke control strategy in a confined space, a fire of about 4.0 MW was found to require a ventilation velocity

Table 2
A list of some important full-scale fire experimental studies on heat and POC spread.

Reference	Fire source	Location	Method of determination of HRR	Estimated HRR Value
(Newman, 1984)	Heptane Coal with Kerosene Neoprene (Conveyor belt) with coal and methanol	Not stated	Not stated	10.0 KW – 20.0 MW
(Hansen and Ingason, 2013a)	UG wheel loader/LHD unit and development drilling rig (Jumbo)	Underground facilities of Björka Mineral AB on the outskirts of Sala, Sweden	Oxygen consumption calorimetry (OCC)	15.9 MW for the loader, and 29.4 MW for drilling rig
(Zhou et al., 2018)	Diesel pool and conveyor belt	Safety Research Coal Mine at NIOSH, USA	Fuel mass loss rate	Max of 90.0 kW for belt fire and 350.0 kW for diesel fire
(Laage and Yang, 1991)	Wood and diesel pool	Waldo Mines, USA	Convective heat flux	Max HRR= 50KW for diesel. No report on HRR for wood.
(Cafaro and Bertola, 2010)	Gasoline pool	Colli Berici tunnel, Italy	Fuel mass loss rate	2 – 4.5 MW
(Lönnermark et al., 2012)	Commuter train	Brunsberg tunnel, Sweden	OCC	76.7 – 77.4 MW
(Ingason et al., 2015)	Diesel pool and HGV trailer mock-up	Runehamar tunnel, Norway	OCC	66 – 202 MW
(Haack, 1998)	Vehicles (Passenger car, Bus, HGV, Railway coaches)	EUREKA Project (Repparfjord Tunnel, Norway)	OCC	3 – 100 MW
(Lemaire and Kenyon, 2006)	Fire pools (heptane and toluene) and vehicles	Second Benelux Tunnel, Netherlands	Mass loss rate	0 – 25 MW

up to 1.1 m/s to prevent back-layering (Deckers et al., 2013). Likewise, in another study involving a model tunnel (4.0 m long, 0.6 m wide, and 0.6 m high), with multiple fire sources, a velocity of 0.57 m/s was found to be critical for a 6.0 KW fire (Weng et al., 2015).

The size of the fire, the rate of heat release, the size of the mine drift, the placement of the fire, and the existence or absence of a smoke extraction point are other factors that affect the back-layering length. The combination of some or all these factors has led to the development of different empirical and numerical models for predicting smoke back-layering length. In one of the studies, an analytical model for predicting smoke rollback was developed for a tunnel taking into account both longitudinal ventilation and point extraction ventilation (Wang et al., 2018). Their model considered both the mass flow rate of the smoke and the separation between the fire and the smoke vent. The HRR, the longitudinal velocity, the velocity at the exhaust, and the dimension (width and height) of the tunnel were also considered. The key findings from their studies indicate that minimizing the separation between the smoke vent and the fire could decrease the back-layering length and the effect becomes more pronounced for higher vent velocity.

Furthermore, the effect of tunnel inclination was modeled, and a new model to predict back-layering length for tilted tunnels was developed (Zhang et al., 2021). The study used fire dynamic simulator (FDS) to simulate nine different tunnel slopes from 0.0% to 8.0% to investigate smoke flow characteristics in the tilted tunnels under natural ventilation. It was observed that the length of the smoke back-layering in the downhill direction decreased with increasing tunnel slope. A similar study investigated a model tunnel with a 4.0% slope and obtained analogous results (Kong et al., 2021). Their established model suggests that the dimensionless smoke rollback length is logarithmically related to the downstream length to the cubic power, and the predicted values agreed with the simulations' results for a tunnel slope of 3.5 – 7.5%. In the same vein, a more robust model which incorporates the effect of the vertical shaft for inclined tunnels was developed by the Wan research group (Wan et al., 2019). The research attempted to unravel the phenomenon of plug-holing for tunnels with a slope from 5.0% to 25.0% and the results indicated that plug-holing decreases as the slope of the drift increases. Summarily, back-layering lengths have been generally observed to show an exponential relationship with tunnel slope for inclined tunnels (Kong et al., 2022), and numerous empirical models have been proposed to quantify back-layering length in underground mine drift/tunnels. From a critical review, the existing models can be classified based on the parameters in Table 3.

Table 3
Classification of back-layering model based on tunnel configuration.

Parameter	Subclass	
Tunnel inclination	Horizontal	Inclined
Ventilation	Natural	Longitudinal
Smoke Exhaust shaft	Present	Absent

The most commonly used back-layering length model was developed by Li et al.(Li et al., 2010) for longitudinally ventilated tunnel and it is given by Eq. 1:

$$L_b^* = \begin{cases} \left(18.5 In\left(0.18 Q^{*\frac{1}{3}} / V^*\right), Q^* \leq 0.15\right. \\ 18.5 In\left(\frac{0.43}{V^*}\right), Q^* > 0.15 \end{cases} \quad (1)$$

While the slope effect for black layering can be expressed as shown in Eq. 2 (Kong et al., 2021; Oka et al., 2013).

$$\frac{L_b}{Q^{2/5}} = 3.18\theta^{-0.56} \quad (2)$$

Models for other scenarios of mine configuration and the location of the smoke extraction point can be derived by combining the above equations to measure the back-layering length. In the Runehamar tunnel fire tests for instance, the results show that smoke back-layering length could be up to 100 m or more for an HRR between 66 MW and 202 MW with a longitudinal ventilation velocity of about 2.0 m/s (Ingason et al., 2015). Another full-scale study involving a commuter train in a Swedish tunnel successfully measured the arrival time of smoke which could help to determine back-layering length due to fires in tunnels (Lönnermark et al., 2012). Whereas, some other researchers have applied a numerical approach to measuring back-layering length. In one study, it was observed that the back-layering length could be up to 15.0 m in a 72.0 m long tunnel for HRR values between 40 and 160 KW, and longitudinal ventilation velocity of 0.2–0.8 m/s (Wu et al., 2018), while the observed back-layering length was about 9.0 m when the same tunnel configuration was used in another similar study where a ceiling smoke extraction system was present in the tunnel (Chen et al., 2015). Overall, the literature points out that the measured back-layering length depends on several factors principal of which are HRR, ventilation, and tunnel geometry.

3.3. Impacts of combustible materials

The nature of the combustible material is a crucial property that affects fire behavior. In most fire experimental studies, diesel and gasoline are used as the combustible materials (Babrauskas, 1983; Beard et al., 1999; Cafaro and Bertola, 2010; R. R.O. Carvel et al., 2001; R. Carvel et al., 2001; Cheng et al., 2001; Chow et al., 2008; Thomas, 1963; Yuan et al., 2016; Zhang, 2012). Some extreme cases involve the burning of abandoned mining vehicles underground (Hansen and Ingason, 2013a; Li et al., 2010). Other materials have also been used including wooden cribs, belts, coal, etc. For instance, wooden cribs were used by Ingason and Li (2010a) in a series of twelve tests to examine the effect of longitudinal ventilation on tunnel fires. Another similar experimental study used a heptane pool of diameter 0.35–0.70 m to investigate fire pool characteristics (Poulsen and Jomaas, 2012). Zhou et al. (2018) conducted fire tests for diesel pool cases and a belt to perform a validation study on the capability of MFIRE in modeling carbon monoxide for underground mine fires. In the study, a pan (32 in. by 44 in.) was used to burn 7.6 l (2.0 gal.) of diesel for the diesel test while the conveyor belt was cut into 48 pieces sized 7.6 cm × 7.6 cm for the conveyor fire test during the experiments.

4. Fire characteristics and calculation procedures

After fire experiments are conducted, fire characteristics are further analyzed by the determination of some key factors. This section presents the methodologies used for such calculations and analyses.

4.1. Heat release rate (HRR)

The heat release rate is the most important parameter used to describe the behavior of fire and could be calculated by using different calorimetry methods or mass loss rate techniques (Brohez et al., 2000; Huggett, 1980; Khan et al., 2016; Tewarson, 1980). However, two major approaches have been mostly adopted for calculating HRR for mine fires. The first approach is based on oxygen consumption calorimetry (OCC) proposed by Hugget (Huggett, 1980) and has been adopted in a couple of fire research studies (Hansen and Ingason, 2013a). The OCC has been successfully adopted to measure HRR in mine fire experiments for both full-scale and small-scale experiments. This approach assumed that the local gas temperature and the local gas concentration can be related as shown in Eqs. 3 and 4.

$$\dot{Q} = \frac{13100 \times \rho_0 \times \mu_0 \times A \times \left(\frac{M_{O2}}{M_a}\right) \times \left(1 - X_{H_2O,0}\right)}{\frac{0.1}{X_{O2,0}} + \frac{1 - X_{O2,avg} \times \left(\frac{X_{O2,avg}}{1 - X_{CO2,avg}}\right)}{X_{O2,0} - \left(X_{O2,avg} \times \left(\frac{1 - X_{CO2,0}}{1 - X_{CO2,avg}}\right)\right)}} \tag{3}$$

$$\mu_0 = \mu_{avg} \times \left(\frac{T_0}{T_{avg}}\right)[m/s] \tag{4}$$

where T_0 is the ambient temperature [K], T_{avg} is the average temperature in a mine airway [K], A is the cross-sectional area [m^2], M_{O2} is the molecular weight of oxygen, and μ_0 represents the cold gas velocity in a mine airway [m/s] and μ_{avg} is the average longitudinal velocity in a mine drift [m/s]. The molecular weight of air is M_a. $X_{H_2O,0}$ represents the mole fraction of water in the surrounding air, X (O2, avg) represents the average oxygen content, and $X_{CO2,avg}$ represents the average carbon dioxide concentration. The mole fractions of oxygen and carbon dioxide in the surrounding air are $X_{O2,0}$and $X_{CO2,0}$ respectively. The second technique of calculating the heat release rate is by measuring the changes in the mass of the fuel with the burning time (Zhang, 2012; Zhou et al., 2018). This technique is frequently used to measure the HRR in underground fire experimental studies. The mass loss rate is measured by using a digital scale that can continuously record the weight of fuel during the experiment. The HRR can then be calculated as given in Eq. 5.

$$Q = m^{'}\Delta H_{c,eff}\left(1 - e^{-k\beta D}\right) \tag{5}$$

where D is the diameter of the burning area (in m), $k\beta$ is the empirical constant (in m^{-1}), and $m^{'}$ symbolizes the burning rate or mass loss rate per unit area per unit time ($kgm^{-2}s^{-1}$), $\Delta H_{c,eff}$ represents the effective heat of combustion (kJ.kg-1). Eliminating the element in parenthesis from the equation would simplify it further, and the HRR could be calculated from the mass loss rate of the combustion product as shown in (Yuan et al., 2016).

4.2. Flame height

(Bubbico et al., 2016; Thomas, 1963; Zhen and Xiaolin, 2014) describe the correlation that is most frequently employed to determine the height of the flame. The method calculates the flame height by using a relationship between the diameter of the pool and the fuel-burning rate. Other methods include a correlation developed by Heskestad in 1995 (Marková et al., 2020), which employs the relationship between the heat release rate and pool diameter while Miao et al.(Miao et al., 2014) developed an even simpler correlation that only requires the pool diameter to determine the flame height. A list of the widely used correlation for determining the flame height is presented in Table 4. One may refer to (Lam and Weckman, 2015; Salvagni et al., 2019; Salvagni et al., 2020) for further reading on flame characteristics and determination.

4.3. Flame length

The flame length could be defined as the horizontal distance from the center of the fire source to the flame tip (Ingason and Li, 2010a). Only a few attempts have been made to determine an empirical correlation for flame length. The method that is frequently employed to determine flame length is based on the work of Rew and Deaves (Rew and Deaves, 1999). They primarily used information from the Channel Tunnel Fire in 1996, as well as findings from the HGV-EUREKA 499 fire test and the Memorial Tests. The empirical correlation derived is stated in Eq. 6 where Q and V denote the HRR and ventilation velocity respectively (Ingason and Li, 2010a).

$$L_f = 20\left(\frac{Q}{120}\right)\left(\frac{V}{10}\right)^{-0.4} \tag{6}$$

Although the above equation is suitable to be applied in mine fire scenarios since most of the equipment in the underground are HGVs, however, this equation has a drawback in that it does not consider any geometrical parameter. This limitation makes it impossible to apply the correlation in predicting the flame length in other tunnels due to the different geometries of tunnels and fire sources associated with underground mines.

Table 4
List of empirical correlations for flame height determination.

Reference	Empirical correlation	Definition of parameters
(Bubbico et al., 2016; Marková et al., 2020; Thomas, 1963; Zhen and Xiaolin, 2014)	$\frac{H}{D} = 42\left(\frac{m^{'}}{\rho_a\sqrt{gD}}\right)^{0.61}$	H= flame height (m) D= pool diameter (m) $m^{'}$= burning rate ($kgm^{-2}s^{-1}$) ρ_a= density of air (kg/m3) g=acceleration due to gravity (m/s2) Q= heat release rate. (kW)
(Marková et al., 2020)	$\frac{H}{D} = 0.235\frac{Q^{2/5}}{D} - 1.02$	
(Marková et al., 2020; Miao et al., 2014)	$\frac{H}{D} = 1.73 + 0.33D^{-1}$	

4.4. Heat flux

According to (Ingason and Li, 2010a; Ingason and Wickström, 2007), the heat flux to an object at a given position from fire in mines can be calculated from the equation given below.

$$q_{inc}^{'} = \frac{\varepsilon_{PT} \times \sigma \times T_{PT}^{4} + (h_{PT} + K_{cond}) \times (T_{PT} - T_0) + \rho_{st} \times c_{st} \times \delta \times \frac{\Delta T_{PT}}{\Delta t}}{\varepsilon_{PT}} \, [kW/m^2] \tag{7}$$

where σ is the Stefan-Boltzmann constant, 5.67·10–11 $kW/m^2 \cdot K^4$, ε_{PT} denotes the surface emissivity of the plate thermometer, which was estimated to be 0.8 (Hansen and Ingason, 2013a), T_0 is the temperature of the surrounding air[K], ρ_{st} denotes the density of steel assumed as 8100 kg/m^3, c_{st} represents the specific heat capacity of steel [J/kg·K], which was set to 460 J/kg·K, δ is the thickness of steel plate [m], given as 0.0007 m (Ingason and Wickström, 2007), and t is the time [s]. T_{PT} represents the temperature of the plate thermometer [K], h_{PT} is the coefficient of the plate thermometer for convective heat transfer, [$W/m^2 \cdot K$], which is given as 10.0 $W/m^2 \cdot K$ (Ingason and Wickström, 2007), K_{cond} is a conduction correction factor [$W/m^2 \cdot K$], which was estimated to be 22.0 $W/m^2 \cdot K$ (Hansen and Ingason, 2013a).

5. Mine fire simulation and hazard analysis methods

Mine fire simulation and hazard analysis techniques could be classified into three categories as shown in Fig. 5: 1D mine ventilation network fire simulation, computational fluid dynamics (CFD) fire simulation, and hybrid fire simulation that combines the above two methods (Vermesi et al., 2017).

5.1. 1 D mine fire simulation

Fires simulation using 1D ventilation networks such as MFIRE is well documented in the literature (Chang et al., 1990; Cheng et al., 2001; Hardy and Heasley, 2006; Laage and Yang, 1995; Zhou, 2009; Zhou et al., 2016; Zhou et al., 2018).

Mine fires could be simulated using 1D mine ventilation network analysis tools. These tools are simple to use, quick to run and computationally inexpensive. The oldest 1D mine fire simulation package is the MFIRE program. Others popular 1D ventialtion network analysis packages include VnetPC and Ventsim. The MFIRE mine ventilation network analysis could be used to simulate fire accidents in underground mines (Cheng et al., 2001; Laage and Yang, 1995), and the development of analog computers in the 1950 s and 60 s led to a more robust analysis of mine ventilation network. Although, the first attempt to simulate the interaction between mine fires and ventilation network could be traced to (Greuer, 1977) and by 1981, a computer program that could solve mine fires and ventilation interaction problems using steady-state analysis was developed (Laage and Yang, 1995; Zhou, 2009). The program named MTU/BOM was developed by a group of researchers at the Michigan Technological University in conjunction with the U.S bureau of mines. Since the development of MFIRE, it has undergone several modifications, and the latest one is called MFIRE 2.30 which was later developed by (Zhou, 2009).

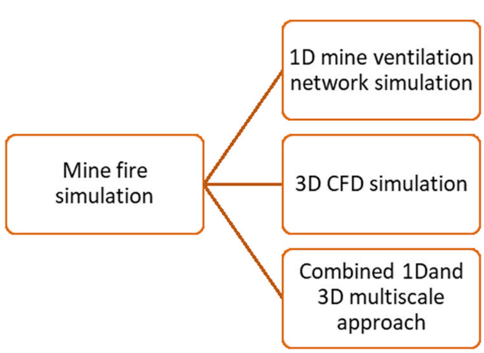

Fig. 5. Classification of mine fire simulation technique.

The current version of MFIRE, MFIRE 2.30 is more sophisticated and has better predictive capability compared to the previous version developed. It introduced a t-squared fire model to account for the variability of the heat release rate of mine fires. In addition, it also accounted for the effect of smoke roll back and heat release from moving source such as the conveyor belt. Perhaps the greatest improvement of the MFIRE 2.30 was the recoding of the original MFIRE program in object-oriented C+ +. The previous version of the program was written in FORTRAN to run on a DOS environment and it was in danger of being incompatible with the latest computers that run on the Windows Vista environment (Chang et al., 1990; Zhou et al., 2016; Zhou and Smith, 2012).

MFIRE could be used to plan for emergency evacuation in an event of a fire accident in underground mines. It could be used to predict the spread of carbon monoxide in an underground mine thereby helping in fire emergency planning (Yuan et al., 2016; Zhou et al., 2020). Carbon monoxide is a major threat to the life of miners in the underground and studies have validated that MFIRE could accurately predict the spread of carbon monoxide in underground mines (Yuan et al., 2016; Zhou et al., 2018). Aside from modeling CO spread in the mine, it could also be used to predict the peak temperatures and heat flow to air and rock with a single fixed heat input from a study conducted at Waldo mines (Laage and Yang, 1991). Furthermore, MFIRE could help predict the emergency ventilation technique during a fire outbreak in the underground. (Cheng et al., 2001) employed MFIRE to simulate a hypothetical fire outbreak in the Taipei Mass Rapid Transit System (TMRTS) and proposed that a push–pull ventilation will efficiently exhaust the high-temperature air and smoke out of the underground facilities once a fire breaks out.

Recently, the Ventsim program has gained popularity compared to MFIRE mainly because it possesses better visualization and modeling capabilities for underground mine ventilation analysis (Nematollahi Sarvestani et al., 2023). It is one of the best-selling mine ventilation software which has gained the trust and approval of mines operators, government representatives, researchers, and consultants in the mining industry (Duy Huy et al., 2022). Haghighat and Gillies (Haghighat and Gillies, 2015) applied Ventsim to study the fire and airflow behavior when a Bobcat vehicle is ignited at the working face of a mine. In their analysis, they were able to determine the concentration of CO gas at the closest station to the fire to be about 3000 ppm if all the ventilation fans were turned off. In addition, the investigation identified the most perilous part of the mine based on the fire scenario and this could aid future emergency preparedness. In another study by (Brakea et al., 2015), they analyzed the survivability criteria based on the toxic gas concentration, temperature, and visibility that could impede safe evacuation. They found out that the visibility, wet bulb temperature (WB), and dry bulb temperature (DBT) could significantly impact the survival chances of miners even if they wear the self-contained self-rescuer (SCSR) device.

(Liang et al., 2018) employed Ventsim to examine the spontaneous combustion of coal in an underground coal mine. The study which sought to investigate the air leakage problem in the long-wall operated in multi-seam and under shallow cover at the Bulianta colliery discovered that spontaneous combustion could be mitigated by isolating and pressurizing active long-wall panels. Additionally, the authors found that differential pressure in the colliery could be adjusted by varying the performance of the auxiliary fans and the resistance of the ventilation regulator. These recommendations were made for future field implementation in the Bulianta coal mine. Several other researchers have also used Ventsim for various mine ventilation and fire emergency planning. For example, (Stewart et al., 2015) examined the capability of Ventsim to simulate back-layering phenomena in mines by using a splitting algorithm to create a high-density three-dimensional mesh within the ventilation airway. Previously, (Wei et al., 2011) used Ventsim to design a ventilation management system for a deep underground mine by identifying areas of the mine with large resistance, thus making recommendations for effective management of airflow. Some other researchers have also employed Ventsim in the design and optimization of mine ventilation systems such as the simulation and analysis of multiple fire scenarios conducted by (Brakea et al., 2015), and the modeling of fires in an underground room-and-pillar mine by (Nematollahi Sarvestani et al., 2023).

However, despite the extensive work that has been done with Ventsim and other 1D network models such as MFIRE for mine fire evacuation planning, they are still faced with some major setbacks. One major shortcoming of this simulation is that it cannot be used to predict the behavior of smoke and heat in complex situations. 1D network analysis only considers airflow along one pathway between the ventilation network nodes thereby restricting the smoke, heat, and other product of combustion to one-directional flow which is not practical in real fire scenarios (Stewart et al., 2015). The spread of smoke and toxic gases generated creates a bi-directional flow in the mine or tunnel and may impede firefighting or mine rescue missions. This limitation could be overcome by using CFD because they are more accurate compared to 1D models and could predict the behavior of smoke and heat in complex underground structures.

5.2. Computational fluid dynamics method

The fact that CFD simulations produce more detailed data, such as airflow velocity, pressure, gas concentration, heat flux, temperature, etc., is one of the main benefits of CFD in mine fire safety (Yuan et al., 2016). Therefore, as compared to numerical 1D ventilation network simulation techniques, CFD fire models offer a deeper understanding of complex thermal gas flow and heat transfer concerns. The fire dynamic simulator (FDS), created by NIST primarily to address low-speed flows with a focus on heat and smoke transport from flames, is the most popular CFD software for mine fire research. Below is a discussion of some of the important parameters for CFD fire simulation.

5.2.1. Effect of geometry and obstructions

Experimental measurements and modeling predictions have indicated that blockage/obstructions can greatly influence the critical velocity and temperature distribution along the mine drift (Shafee and Yozgatligil, 2018). For instance, when there is a blockage or obstruction, the corresponding critical ventilation velocity decreases (Gannouni and Maad, 2015; Han et al., 2021; Lee and Tsai, 2012; Meng et al., 2018; Oka and Atkinson, 1995). The reduction is seen to rely on where the obstacles are located on the tunnel floor. When the gap between the obstacle's bottom and the tunnel floor widens, it becomes slightly larger. This phenomenon also accounts for the smaller back-layering length observed in tunnels with obstacles when compared to empty tunnels. In one study, three types of vehicular obstructions were used in a 7.0 m-long tunnel. It was observed that the reduction ratio for the critical velocity approximately equals the vehicle blockage ratio (Lee and Tsai, 2012). Also, Huang et al. (2018) demonstrated through numerical studies that sealing off the entrance of the tunnel is a good tactic for firefighting and improving safety. Because less oxygen is provided when the tunnel is sealed off, their tests demonstrated that the longitudinal ceiling temperature lowers as the tunnel entrance sealing ratio increases. A scenario involving a mine truck fire and miners using brattice obstruction to escape from the underground can be depicted in Fig. 6.

Fig. 6 shows a truck fire along an underground mine roadway and two miners approaching the fire with a brattice barrier in the escape direction. The movable brattice could be deployed to redirect the thermal plume toward the mine ceiling thus improving the escape chance. Some CFD studies have proven that using this technique could also reduce CO concentration and impede smoke arrival rate in underground spaces during an evacuation process. In one study, an obstruction in the form of a brattice barrier which occupies 70.0% of a mine roadway reduced the CO concentration by up to 43.0% and increased the airway visibility by up to 30.0% (Adjiski et al., 2016). Likewise, numerical results show that smoke arrival time significantly increased when obstruction existed in the tunnel. In the investigation, an obstacle occupying about 31.0% of the tunnel cross-section placed at a different distance from the tunnel floor in a 12.0 m long tunnel effectively reduced back-layering length (Gannouni and Maad, 2015).

Similarly, Yu et al. (2016) and Luo et al. (2013) have demonstrated that obstructions like air curtains could help in the confinement of smoke by conducting CFD simulation and experimental studies of fire and smoke flow fields in a wind tunnel. In their study, Yu et al. (2016) analyzed the performance of air curtains in blocking fire-induced smoke by using a momentum ratio parameter "R" to evaluate the sealing effectiveness "E" of the air curtains. For low values of R, it was discovered that the E increased as R increased. On the other hand, higher values of R result in reduced effectiveness since the smoke is pushed downstream by the downward impinging airflow. Similarly, experiments and simulation results showed that air curtains assisted in controlling the discharge and diffusion of smoke (Luo et al., 2013). This was revealed from the observation that the CO concentration at the entrance

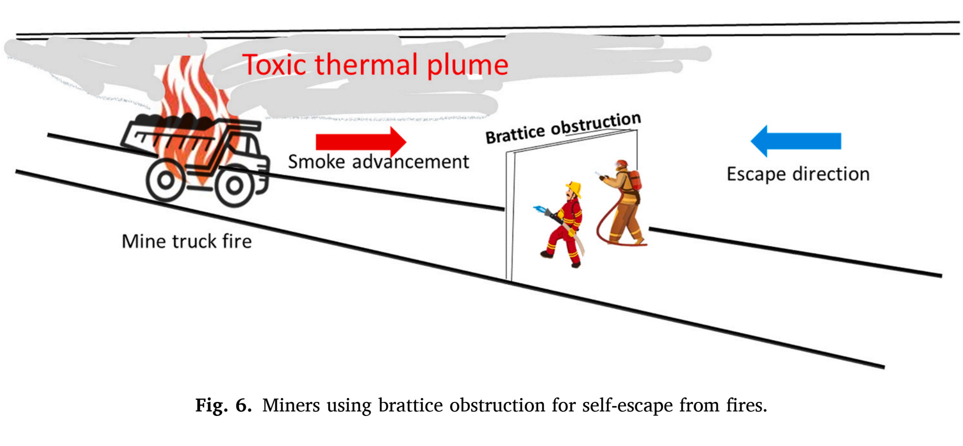

Fig. 6. Miners using brattice obstruction for self-escape from fires.

significantly decreases whenever the curtain is used. Therefore, we can conclude that an optimal evacuation plan could be improved when obstructions are properly utilized in specified locations in the underground operations (Adjiski and Despodov, 2020).

5.2.2. Mesh size

The mesh or grid size used for a CFD simulation depends on the size of the geometry, the desired modeling accuracy, and the level of detail to be obtained. It is the principal factor that determines the resolution of the CFD simulation and could impact properties like fire smoke temperature measured at the airway ceiling. For this reason, appropriate grid sensitivity should be done to obtain mesh independence. In FDS, the grid size can be derived by the fire characteristic diameter given in Eq. (8) (Weng et al., 2015):

$$D^{*} = \left(\frac{\dot{Q}}{\rho_{\infty} c_{p} T_{\infty} \sqrt{g}}\right)^{2/5} \tag{8}$$

where ρ_{∞} designates the ambient air density kg/m^3, δx denotes the nominal size of the mesh cell, $\dot{Q}$ represents the total heat release rate of the fire (kW), C_p is the specific heat capacity of air (KJ/kg/k), T_{∞} is the temperature (K) of the surrounding air, and g is the acceleration due to gravity (usually taken as 9.81 m/s^2) (McGrattan et al., 2016; Overholt, 2014).

The ratio of fire characteristic size to grid size ($D^{*}/\delta x$) known as the plume resolution (PR) index is normally used to describe the quality of the calculation grid (Gannouni and Maad, 2015). The higher this value is, the finer the meshes are. This value is recommended to be in the range of 4–16 based on mesh sensitivity studies from the literature (McGrattan et al., 2016; McGrattan et al., 2014). Although some studies have used values outside of this range, for example, the FM panels test used a value between 12 and 19, the NIST-RSE test used a value of 12–32, the National Research Council of Canada (NRCC) façade test used values of 18–24, while the Sandia Plume fire test used values of 20–118. PR index of 10 or a grid size of 23–92 cm has been widely validated to produce reliable results for tunnel fire modeling (Chen et al., 2019).

Increasing the PR index generally increases the computational time of the FDS calculations and may not necessarily lead to improved accuracy of the prediction. For example, in one of the studies that evaluated mesh sensitivity, increasing PR from 12 to 24 increased the computational time by a factor of up to 5 with a minimal improvement in simulation accuracy (Lin and Chuah, 2008). For this reason, a multi-grid system can be used to minimize computational resources while maintaining accuracy for large domains. In a study that investigated the effectiveness of tunnel entrance sealing ratio on the fire behavior inside a tunnel, a 200.0 m tunnel with a 10.0 m by 3.0 m fire source in the middle was simulated. It used a PR value of 10 for the middle 60.0 m section with the fire source, and a value of 5 for the rest of the model. The longitudinal decay and ceiling temperatures predicted by the model agreed well with earlier experimental findings (Huang et al., 2018). In a simulation study for a 13.0 km long tunnel fire (Chen et al., 2019), δx was set to 25.0 cm for the domain in the fire region while for the other regions, a value between 50.0 and 100.0 cm was adopted while maintaining a sufficient resolution.

5.2.3. Turbulence model

The Reynolds Averaged Navier-Stokes (RANS) and the Large Eddy Simulation (LES) are the major turbulent models widely used in mine fire simulation. The RANS and LES solves the Navier-Stokes equations and are appropriate for modeling low-speed, thermally-driven flow with a focus on the transport phenomenon of heat and smoke from fires (McGrattan et al., 2012).

LES resolves the fire characteristics according to the grid size, whereas the RANS averages the values over significantly larger spatial and temporal scales other than the characteristic given by the numerical grid (Van Maele and Merci, 2008). While some researchers have presented arguments that scenarios like fire plumes, ceiling points, and other low-speed thermally driven flow are best represented by LES techniques, the accuracy of the LES results strongly depends on the quality of the mesh and it leads to more turbulent thermal diffusion when compared to RANS (Van Maele and Merci, 2008). Generally, LES is more accurate than the RANS approach because the large eddies contain most of the turbulent energy, and account for most of the momentum transfer and energy turbulent mixing (Zhiyin, 2015). This is one of the reasons why most of the available fire simulation packages such as FDS and Pyrosim are based on LES (McGRATTAN, 2005; McGrattan et al., 2012). However, the computation time for LES has been observed to be usually higher than that of the RANS models (Zhai et al., 2007; Zhang et al., 2007).

Moreso, there is a possibility that different RANS sub-models give different results (Vasanth et al., 2013). Whereas, for LES, the dynamics of the pool fires from laminar to turbulent transition could be captured without needing to tune or adjust the turbulence model parameters (Maragkos and Merci, 2020). The default settings i.e., the constant Smagorinsky model (where $P_{rt} = 0.5, S_{ct} = 0.5, and C_s$=0.17), is adopted in most studies for the LES. Although, it can sometimes be modified by adopting the dynamic Smagorinsky model where the turbulent parameters such as the turbulent Prandtl number (P_{rt}), turbulent Schmidt number (S_{ct}), and sub-grid scale dynamic viscosity (C_s), are changed.

5.2.4. Selection of fire chemistry

The critical ventilation velocity of the fire is barely impacted by the fire chemistry selection made for the CFD simulation. To assess the impact of fuel on critical ventilation velocity, methane, and propane were employed as fuel in one simulation study for small tunnels and propane and methane for large tunnels (Hwang and Edwards, 2005). However, no significant difference was observed for the critical velocity. Instead, it was discovered that the critical velocity was strongly influenced by the HRR and the tunnel dimension. Even though most of the CFD fire simulations used propane as the fire source, Yi et al. (2013) used methanol as fuel in one study to simulate the fire source. Nevertheless, the choice of fuel is expected to influence the heat release rate of the fire. This is because different fuels have different heats of combustion. Additionally, lighter fuels such as methanol are expected to burn faster and have a corresponding higher mass loss rate compared to more dense fuel like diesel thus influencing the heat release rate.

5.3. FDS Vs other CFD

FDS is an LES-based CFD solver widely used for fire simulation studies. There are two main advantages of FDS compared to other CFD solvers. One is that the solver is designed to solve low-speed thermally driven flow, which is a good approximation for fire in confined spaces. This is because it primarily solves a form of the Navier-Stokes equations appropriate for low-speed flows with an emphasis on smoke and heat transport from fires (Kerber and Milke, 2007). For this reason, FDS has been popularly deployed to model fires with low Mach numbers (Ma< 0.3) such as atrium fire configurations, fires in tunnels, and building fires since all these situations represent confined spaces. In a study, verification of FDS accuracy was conducted for low-speed flow in a small-scale tunnel and atrium fire configuration (Tilley et al., 2011). The numerical simulation results of the atrium height and back-layering distance show very promising agreement with the experiments even though further work is required to verify this. Another study used low Mach characteristics of FDS to conduct a performance-based assessment of a proposed ventilation strategy for a residential block atrium and from the analysis, an effective smoke extraction strategy was developed (Al-Waked et al., 2021).

The other advantage of FDS is that it can provide transient solutions with enough temporal and spatial resolutions using less computational time. This is achieved by using the EDC (Eddy Dissipation Concept) non-premixed combustion model which requires significantly lower CPU times. It could be further enhanced by utilizing the MPI parallel processing capabilities in FDS to decrease the simulations' processing time . For example, in some studies to analyze heat and smoke propagation in a large-scale compartment fire, Fluent requires twice or more CPU times than FDS when standard settings are used (Zanzi et al., 2019). In another study, Verda et al. (2021) used less computational time in a tunnel with a cross-section of 4.8 m and 600.0 m long by incorporating a Whitesmoke code into FDS through direct coupling and still obtained acceptable accuracy. Also, FDS only took about 0.9 h for a CFD simulation that requires 3.9 h in FLEUNT while it still maintained higher accuracy (Gu et al., 2020).

FDS generally performs better when compared to other fire CFD fire solvers. A study evaluated its performance based on hydrocarbon pool fire experiments with pool sizes ranging from 1.5 m to 6.0 m. The fractional bias of $\pm$30% and the normalized mean square error ≤ 0.5 were used as performance criteria to evaluate the level of agreement with experimental measurements. On all the evaluated variables, including flame temperature, burning rate, heat flux, flame height, flame surface, and surface emissive power, it was discovered that FDS performed better than other CFD algorithms. Similar findings were observed in a study comparing FDS and FLUENT when studying ceiling temperature and smoke layer thickness in tunnels (Binbin, 2011; Chiew, 2013). In the subway platform fire study (Binbin, 2011), it was found that the FLUENT prediction was much higher than the measured values and has greater fluctuations in the temperature curve when compared with FDS. Even though the FDS predicted a lower temperature compared to measured values, the results were found to be within $\pm$20%. The study indicated that Fluent over-predicted the temperature for points 1.0 m high and above in a room that is 3.0 m high. On the contrary, FDS and Fluent show reasonable agreement in the investigation conducted by Zanzi et al. (2019), despite the observed proximity in temperature results for a large compartment fire in an underground transportation hub, FDS still showed superiority in simulating the mass flow rates of cold air coming through natural vents and the mass flow rates of CO_2 through the west vent and forced ventilation grilles.

Furthermore, many other studies have evaluated the accuracy of FDS modeling against full-scale fire experiments in mining scenarios. FDS was used to unravel the behavior of self-heating coal and its combustion characteristics in the gob area thereby, providing useful information about the potential environmental threats in an underground coal mine (Fernández-Alaiz, Castañón, Gómez-Fernández, Bernardo-Sánchez et al., 2020; Fernánez-Alaiz et al., 2020). In the paper, an experimental procedure was established to investigate potential collapse situations in an underground coal mine using a sub-level method. The setup was reproduced in the laboratory scale and FDS was used to assess the behavior of a possible fire and the results were validated with experimental data. In another study, FDS was used to simulate mining vehicle (a loader and a drill rig) fires in an underground mine drift based on full-scale experiments (Hansen, 2020). Although the FDS predicted a much higher temperature compared to the full-scale test, the prediction values were still within $\pm$ 30%. The higher prediction values were attributed to the choice of radiative fraction values adopted and studies have shown that radiative fraction should be analyzed based on fire time and size before modeling fire. A value of 35% is generally acceptable for the radiative fraction from the literature. However, reducing the radiative fraction from 0.35 to 0.00 brought the predicted peak temperature of FDS from 225 °C down to 100 °C in an investigation. This implies that the radiative fraction parameter has a significant effect on the FDS simulation output (Jahn et al., 2008).

The major limitations of the FDS are in its meshing capabilities. FDS is not very efficient in modeling complex geometry and regular building blocks are mostly used for mesh generation (Binbin, 2011). Other CFD solvers for fire simulation such as FireFOAM and FLUENT could incorporate general structured or unstructured polyhedral meshes thereby improving the accuracy of the simulation results (Trouvé and Wang, 2010). The FDS can only use rectilinear meshes in fire simulation, so the mesh geometry is restricted to multi-block rectangular cartesian coordinates. Therefore, a very fine mesh must be created by increasing the number of cell sizes to represent a smooth curvature that impacts the simulation time.

5.4. Multi-scale approach

In a series of fire tests, (Zhang, 2012) developed a hybrid approach otherwise known as a multiscale approach by combining 1D and 3D models to simulate underground mine fire. The multiscale approach is based on the domain decomposition method which has been developed for discretization techniques such as finite difference, finite volume, and finite element methods. They are mainly in the framework of parallel computing and allow the original single problem to be reformulated on several computational sub-domains. In the study, two case scenarios were presented to demonstrate that the multi-scale approach is a reliable way of simulating a complex mine fire and the airflow behavior such as throttling and buoyancy effects during a fire disaster. The result from the study shows that the multi-scale methods produced a superior model when compared to the 1D or 3D used independently.

The multi-scale method has several advantages such as a significant reduction in the computation time and improved accuracy of the results (Haghighat, 2017; Haghighat et al., 2018). Nevertheless, the approach is not without its limitation. For instance, one very important issue about the use of a multiscale model for mine networks with fires depends on the accuracy of pinpointing interfaces between the 1D and 3D models. These boundaries must be in regions where the temperatures or velocity gradients are infinitesimal or negligible, and the flow behaves majorly as in the 1D simulation(Zhang, 2012). These determine the size of the 3D domain and are case-specific but generally depend on the geometry of the mine airway.

In another fire experimental study by (Yuan et al., 2016), Fire Dynamic Simulator (FDS) and MFIRE were used to study the spread of CO in the underground. Full-scale fire experiments were conducted in the NIOSH Safety Research Coal Mine (SRCM) to evaluate different sensors for mine fire detection using an Atmospheric Monitoring System (AMS) in this study. CO modeling is very important since it is usually released when a fire occurs underground. The spread of CO gases through the ventilation network greatly impairs the safe evacuation of miners from the underground facility. Both CFD simulation and Mine Fire simulation were conducted in the study. This is because even though the CFD model can simulate a mine fire and smoke spread to a very large extent, the model lack capability of simulating the smoke spread in a mine ventilation network consisting of numerous airways common in any modern U.S. mines. This is because of the huge number of mesh cells that are needed to obtain reliable CFD results.

Similarly, (Adjiski et al., 2015) applied CFD to model fire scenarios in a mine and MFIRE to optimize evacuation routes in case of fire in underground mines. In the study, the author prepared a 3D model of the mine which includes the actual dimensions and its associated elements which the fire dynamics and evacuation system depend upon. A 3D underground mine drift with a width of 4.0 m, height of 3.0 m, and length of 50.0 m was used for the simulation. A working machinery, Boomer 281, was assumed to be the fire source, in which hydraulic fluid will leak from the tank before ignition. The fire characteristics data obtained from the Pyrosim fire model was used as input in the MINEFIRE PRO+ for the optimization of evacuation routes. This approach could be used to plan evacuation and rescue in case of fire accidents in underground mines.

6. Existing emergency evacuation planning strategies from underground fires

Studies to assess, quantify, and model fire emergency evacuations can be classified into two main categories. They are the optimization approach, and the risk assessment and evaluation methods (see Fig. 7).

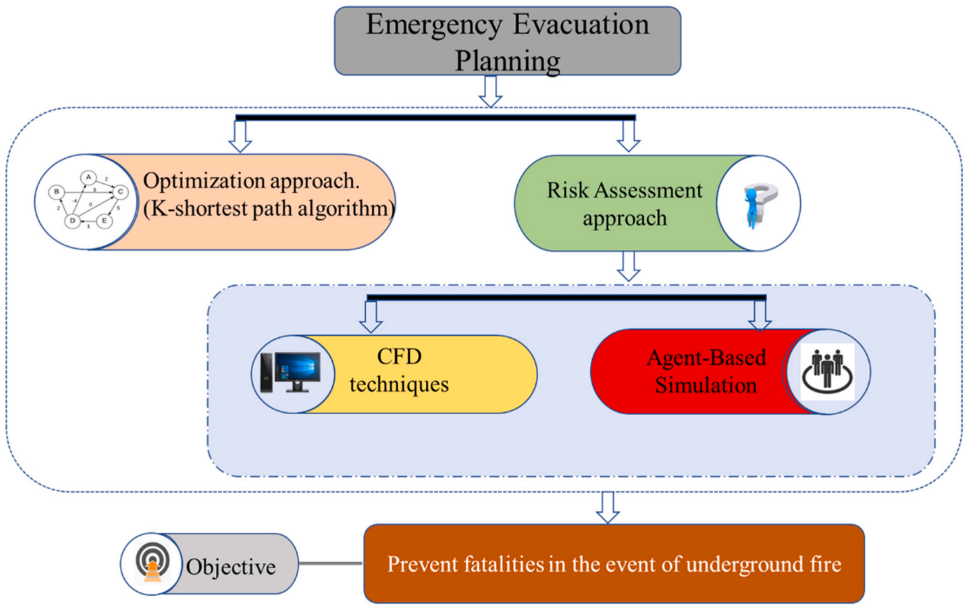

Fig. 7. Summary of existing mine fire evacuation planning methods.

The optimization method focuses primarily on developing an improved algorithm for identifying the shortest distance between any two points while the risk assessment approach involves risk evaluation using simulation tools. The optimization algorithm mainly tries to find the shortest path to safety from any location without considering the dynamics of the fire. Moreover, the shortest path might not be the safest path. The risk evaluation method, on the other hand, involves computer simulation of different combinations of fire properties at different locations underground to determine the worst possible scenario in an event of a fire outbreak. This method is further divided into two main sub-categories which are: fire numerical simulation and personnel evacuation simulation. Regardless of the methods, different techniques aim to solve a single objective problem- to minimize casualties during a fire disaster and safely evacuate occupants in an underground structure. A more recent technology that has been deployed mostly for Australian and Swedish mines for mine emergency evacuation assessment and planning is the Mobilaris Emergency Support (MES) developed by Epiroc. The system provides a highly versatile and connected communication system that has the capability of sending messages to miners during an emergency and keeping track of miners who are aware of the emergency and those that are not while visualizing the whole process in real-time. From the virtual interface, all movement of personnel can be monitored, and miners could be guided to refuge chambers and evacuated as quickly as possible according to defined procedures. The EMS has been adopted as a standard emergency device in Swedish UG mines and it has proven to reduce the evacuation time by 25–50% (Epiroc, 2023).

6.1. Optimization approach

The optimization approach for underground evacuation planning is primarily based on the Network Path Planning Strategy (NPPS) which uses the k-shortest path algorithm. Numerous optimization algorithms have been developed so far to improve the safe egress of occupants from a confined environment (Adjiski and Despodov, 2020; Eppstein, 1998; Hong et al., 2018, 2019; Jalali and Noroozi, 2009; Jin et al., 2013; Zheng and Liu, 2019). The optimum solution could either be applied to maximize exit usage efficiency or minimize the egress time depending on the optimization procedure adopted. For instance, the path planning method was used to develop a 3D constrained space model to establish a priority route for evacuation in constrained space scenarios (Hong et al., 2019). In the study, the confined space was modeled as a 3D connected graph, and a priority-oriented network planning algorithm was constructed to maximize evacuation exit utilization efficiency and minimize the whole evacuation delay. In a similar study, multi-objective dynamic route network planning was introduced to solve emergency evacuation problems in restricted spaces such as the underground (Hong et al., 2018). The study evaluated a multisource to multi-destination evacuation model in confined spaces with the objectives of minimizing the whole evacuation delay and maximizing evacuation efficiency. Furthermore, two different optimization techniques were adopted to develop safe egress for emergency evacuation in an underground space. To discover the quickest pathways between the accident site and safe locations in a network of underground mines, the Floyd-Warshall and Pi optimization algorithms, which are based on the K-shortest path, were implemented in the first study (Jalali and Noroozi, 2009) while in the other paper, deep reinforcement learning was employed to develop a multi-agent deep deterministic policy gradient algorithm that could search for optimal evacuation route during a disaster (Zheng and Liu, 2019). A proper evaluation of the methodologies indicated that although both methods have a common goal, they achieved their objective using different approaches. For instance, the Floyd-Warshall and Pi algorithms formulate the problem on a directed and weighted graph. In the first approach, the shortest escape time between every two given points is determined and assigned as the access route while the latter approach employs four main steps which include modeling the crowd and the environment, grouping the crowd and selecting a leader, hierarchical path planning, and finally followed by the analysis of the evacuation results. As computing ability continues to grow, more improved optimization algorithms could be developed and sometimes an ensemble of different algorithms using machine learning could be adapted to improve fire safety in underground environments (Guo and Zhang, 2022).

6.2. Risk assessment methods

Risk assessments for fire evacuation can be done by various means which range from simple hand calculations involving egress time concept, numerical fire simulation using CFD, or more robust simulation modeling methods involving personnel evacuation using Agent-Based models (ABMs).

6.2.1. Empirical calculations

Some empirical formulae have been proposed to evaluate fire and evacuation risk in confined spaces. For instance, available safe-egress time (ASET) and required safe-egress time (RSET) was proposed to determine the evacuation risk from underground fires (Wang et al., 2021; Zhang et al., 2016). The ASET is defined as the time duration from which the fire starts to the point where occupants could no longer be evacuated while RSET is required time to evacuate occupants to a safe zone once a fire occurs. The ASET could be represented as a function of the minimal time for the CO concentration to reach the threshold limit as follow.

$$ASET = \min(T_{co}, T_{temp}) \tag{9}$$

Where T_{co} indicates the time for CO to reach a threshold value of $5 \times 10^{-4} mol/mol$, while T_{temp} represents the time taken for the smoke temperature to reach a critical value of $60^o C$. On the other hand, the required safe egress time could be further decomposed as follow.

$$RSET = T_r + T_{pre} + T_m \tag{10}$$

Here, T_r is the recognition time (that is the time from when the fire occurs to when the occupants get the fire alarm notification), T_{pre} denotes preparation time for evacuation upon receiving alarm notification, and T_m indicates the duration from when evacuation begins to the end of the evacuation process. By determining the ASET and RSET for designing fire scenarios in an underground structure, one can evaluate the risk level and make recommendations as to how safe egress could be improved for each scenario. On the other hand, some researchers introduced a novel four dimension parameter system that incorporates Average Evacuation Time (AET), Average Waiting Time (AWT), and Average Moving Distance (AMD) in addition to the Required Safety Egress Time (RSET) to quantitatively describe the evacuation from four aspects (Chen et al., 2021). The study proposed a dimensionless parameter, Risk Index (RI) for the risk evaluation and comparison, and the findings show that the RI for AWT is distinctly higher than other Risk Indexes based on twelve designed scenarios and over 600 simulation runs.

Another risk assessment technique is to determine the route of minimal CO emission since most fatalities from mine fires can be attributed to CO and smoke inhalation (Yuan et al., 2016; Zhou, 2009). Evacuation planning was successfully carried out by simulating different fire scenarios and locating the optimal evacuation routes based on minimal exposure to carbon monoxide CO during the evacuation process. In one of the papers, the optimal evacuation route was established by estimating the CO concentration over time in different routes based on different fire simulation scenarios. Additionally, in other to account for the cumulative effects of CO inhalation, the CO concentration was presented in a weighted format using a fractional effective dose (FED) (Adjiski and Despodov, 2020). The study showed that knowing the minimal CO exposure route could help enhance emergency planning and save miners' life during an underground fire.

6.2.2. Fire numerical simulation using CFD

CFD has been successfully used to simulate tunnel fires and has accurately predicted the temperature in the mine airways and tunnels thus improving tunnels and underground fire safety practices (Adjiski et al., 2016; Cheng et al., 2016; Guo and Zhang, 2014; Hwang and Edwards, 2005; Yuan and Smith, 2009, 2015). In one study two full-scale fire tests were conducted in the Colli Berici tunnel and the gas temperature was measured at a different location for the different tests and similar results were also obtained from the CFD simulation (Cafaro and Bertola, 2010). Similarly, Rahmani et al.(Rahmani et al., 2004), applied CFD using large eddy simulation to study fire in tunnels and examined the temperature profile in a model tunnel (25.0 m long by 2.0 m wide by 1.0 m height) to verify the reliability of the CFD model while a combination of experimental analysis and CFD simulation was used to study fire propagation in a sublevel coal mine by (Fernández-Alaiz, Castañón, Gómez-Fernández, Bernardo-Sánchez et al., 2020; Fernánez-Alaiz et al., 2020). The various studies indicated that CFD analysis is a reliable way of understanding the fire risk and thus emergency evacuation strategies could be developed based on the simulations results. For example, in one of the studies, three different scenarios were examined and CFD successfully modeled the evolution of fire in the mine (Fernández-Alaiz, Castañón, Gómez-Fernández, Bernardo-Sánchez et al., 2020; Fernánez-Alaiz et al., 2020). Furthermore, (Woodburn and Britter, 1996) used CFD to simulate tunnel fire and (Yuan and Smith, 2009) modeled spontaneous heating in a large coal chamber using CFD and the studies showed that CFD demonstrated good predictive performance for fire and heat simulation.

Unlike the optimization approach which primarily focuses on the shortest path, CFD has superiority in that it can be applied to analyze smoke spread and reverse flow conditions in addition to temperature evolution (Hwang and Edwards, 2005; McGrattan et al., 1998; Zhou et al., 2018) which is the major cause of casualties in the underground. For example, a major question that often comes to mind is how to apply the optimization algorithm if the fire occurs along the shortest path and the shortest path is smoke-filled which could lead to the death of the miners. With CFD however, ventilation conditions and back-layering phenomenon can be understood, and appropriate emergency response can be developed. CFD was used to predict CO spread in an underground mine and the experimental results validate that FDS could efficiently and accurately predict the spread of smoke in the underground (Yuan et al., 2016). A similar result was also obtained from the CFD simulation of back-layering during a tunnel fire test (Cafaro and Bertola, 2010). Several other studies have employed CFD to develop an emergency evacuation plan during a fire disaster. For example, a CFD model was created to predict the suppression of a conveyor belt fire with water spray (Yuan and Smith, 2015). The model was validated using extensive experimental data that combined the suppression action of water spray with the spread of flames. From the findings, it can be concluded that CFD successfully predicted emergency strategies such as the location of the sprinkler and their activation temperature. More so, the work of Adjiski et al. (2016) further demonstrated that CFD could be a very versatile tool for underground mine fire modeling by employing it to investigate the effectiveness of brattice barriers for underground firefighting and hazard mitigation.

6.3. Agent-based modelling approach

Over the past two decades, interest in a novel modeling technique known as agent-based modeling and simulation (ABMS), or simply agent-based models (ABMs), which models a system as a collection of autonomous decision-making agents, has increased (Bonabeau, 2002; Dong et al., 2022; Macal and North, 2009). Such models have a symbiotic relationship with computing technology and more sophisticated models have now become feasible since more complex algorithms, toolkits, and libraries have been developed (Gilbert and Bankes, 2002). A schematic workflow interaction of miners as agents in a typical agent-based evacuation model for underground confined space is presented in Fig. 8.

From the illustration depicted in Fig. 8, the miners are the agents. Each miner has a set of attributes, rules, behaviors, and memory unique to them. Also, each miner can freely communicate with every other miner due to agent-agent interactions. One significant advantage of this novel method is that it encompasses the fire field data (which include temperature, heat, smoke, and fire gas) obtained from full-scale experiments or validated CFD modeling alongside their interactions with the geometrical properties associated with the confined space in question. The simulation is conducted in a virtual 3D viewer platform such as pathfinder. The 3D viewer platform is a virtual reality platform and could help us further analyze how agents interact in an event of a fire and prepare for subsequent evacuation. By simulating personnel

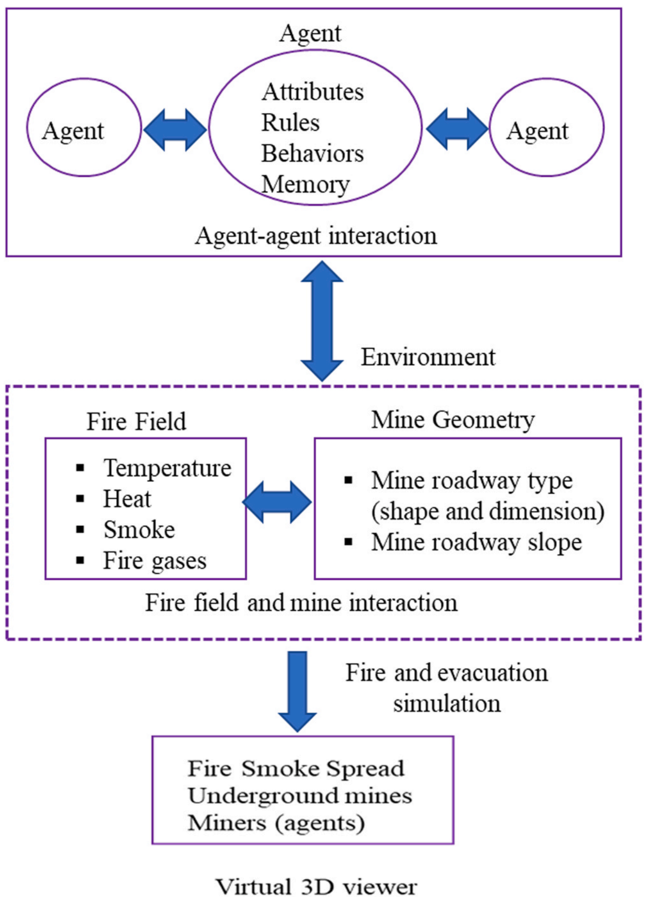

Fig. 8. A schematic of agent-based evacuation strategies for underground confined spaces.

evacuation with ABMs, we can have a better understanding of the interactions of the agent with their environment during a fire emergency, thereby improving fire safety preparedness in the undergrounds.

Just like CFD application in scenario analysis to determine the risk level for different fire situations, ABMs can be used to visualize how the implementation of various emergency plans influences safe egress during an emergency through comparative analysis. An agent-based model study on the comparative analysis of different evacuation strategies using the GAMA simulation platform and the results indicated that following the evacuation signs is the best strategy in the case that was considered (Nguyen et al., 2013). For this case study, following emergency signs yielded a survival chance of 82.48%, following the crowd yielded a 70.97% survival rate, and following own's paths yielded a much lower survival chance of 58.55%. Similarly, a risk assessment study for evacuees using three blind evacuation strategies was conducted to determine the most suitable escape plan in smoke-filled confinement, and the survival chance from the simulation was analyzed in the research (Nguyen et al., 2013). The three blind evaluation strategies were (1) wall tracking by evacuees (2) evacuees going straight, and (3) random motion of evacuees. The wall-tracking technique was observed to produce a higher rate of survival based on the different risk assessment (RA) parameters considered. The proportion of survivors, the level of toxicity, and the duration of escape are the RA factors that are assessed, and in the instance of a blind evacuation due to smoke spread, the wall tracking technique results in a higher percentage of survivors, a lower level of toxicity, and a shorter escape time.

Additionally, ABMs can model individual evacuee behaviors with varying levels of knowledge about the confinement's internal structure and simulate predictable spatial accessibility that is altered by activated fire safety facilities, which would also enhance fire safety (Tan et al., 2015). In one study, a prototype model was developed to evaluate the influence of spatial change on evacuation performance during a fire emergency. The advantage of this model is that it offers the flexibility of examining the influence of changes that occur in the connectivity of the structure and the evacuee's knowledge of the spatial environment. Each evacuee will be able to select their escape route based on the assumed spatial accessibility. Sometimes, ABMs can be coupled with simplified egress modeling such as a 1D smoke propagation model to further improve fire safety assessment (Ronchi et al., 2019). In this scenario, one-dimensional smoke spread calculations are performed to estimate the visibility conditions, as well as the level of toxic gas concentration produced from the fire and the outputs, which are used as inputs for advanced egress modeling such as the ABMs.

ABMs have been successfully deployed to model fire and smoke spread in underground mines. Li et al. (2015) conducted a study to visualize underground mine fire based on an established cellular automata model. The study sought to investigate fire source combustion and fire fume spread. The temperature was monitored at specific locations in the mine while ABMs successfully measured the subsurface quantities of gases, primarily CO and CO_2, in real-time. The findings indicated that this simulation pathway might be used to predict disasters caused by underground mine fires because the measured values and estimated values agreed very well. Additionally, by visualizing the temporal and spatial changes in temperature and the concentration of hazardous gases, it is possible to determine the hazard area and the extent of the hazard in the event of a fire disaster. In another study, Salarian et al. (2020), employed ABMs to simulate defined scenarios and calculate the evacuation times of passengers in a subway. The study focused on reducing evacuation times in the event of a fire by using a safe zone approach in the "Pathfinder" simulation software. Eighteen different scenarios were examined, and the best evacuation strategy was found by increasing the number of exit doors from 2 to 4 while simultaneously considering the safe zone. On the other hand, Edrisi et al., (Edrisi et al., 2021) demonstrated that ABMs could be used to simulate underground metro station evacuation. Three different exit choice models were developed and compared in the study. The models include the multinomial logit model, the modified multinomial logit model with revising decisions, and the shortest path exit option. The egress times for each model were obtained and compared and the results indicate that the modified exit choice model gives the best result because it has a more realistic representation of human behavior.

Another advantage of ABMs over-optimization and CFD evacuation strategy is that it allows the disaggregation of systems into individual components. These are governed by their own set of rules and individual characteristics thus enhancing better performance and superiority in modeling complex systems (Crooks and Heppenstall, 2012). It also can incorporate fire field data and mine geometry to simulate miners' responses during evacuation (Tang and Ren, 2008; Tang and Ren, 2012). The current underground evacuation model does not consider the evacuee's awareness of the predictable change that could occur in the spatial accessibility of evacuation routes. These shortcomings can be resolved with ABMs. The existing ventilation network models and CFD simulations also neglect the occupants' behavior and evacuees' dynamism in confined spaces like the underground. Again, these limitations can be overcome with ABMs and agent-based simulations have been successfully used to simulate human behavior with predictable spatial accessibility in a fire emergency (Tan et al., 2015). More so, unlike traditional models, ABMs try to represent how individuals and the environmental variables that affect them vary in the space-time continuum and other dimensions. They usually involve processes that we know to be important but that is somewhat complex to be included in simpler models (Railsback and Grimm, 2019). Because of the growing popularity and flexibility of ABMs, many researchers have since considered using agent-based models to plan emergency evacuation from buildings during a disaster although only a few studies have attempted to use ABMs for evacuation in underground mines.

6.4. State-of-the-art practical measures and lessons learned

The Moura No. 2 disaster that occurred in Queensland in 1994 led to the implementation and enforcement of annual level 1 emergency exercises done by UG coal mines in the State of Queensland, Australia since 1998 (Dent, 2002; Halim and Brune, 2019; Hopkins, 2020; Queensland-Government, 2022; Roxborough, 1997). Years later, many other countries including Canada, Chile, China, India, Indonesia, Mexico, New Zealand, South Africa, and the United States have also adopted this type of legislation to mitigate disasters in their mines. The exercises are typically held every year or every two years depending on the country's legislation. In the US, MSHA has mandated that this exercise should be done yearly and the adoption of this of the Queensland model is a testament to the effectiveness of this model. These exercises have helped to improve mine safety in Queensland and around the world. The key lessons learned could be summarized as follows (Queensland-Government, 2022):

- Communication and coordination: In an emergency, everyone involved must be able to communicate effectively with each other. This includes mine workers, mine management, emergency services, and government agencies. Clear and concise communication plans and procedures are essential, as well as regular training and drills to ensure that everyone knows their role in an emergency.
- Emergency kits: A well-stocked emergency kit is essential for any mine. This should include first aid supplies, fire extinguishers, and breathing apparatus. In the event of an emergency, these supplies can be used to save lives.
- Equipment and infrastructure: Regular inspections and maintenance of mine equipment and infrastructure are essential to identify and correct potential hazards. This includes things like ventilation systems, electrical systems, and machinery. By taking steps to mitigate risks, mines can help to prevent accidents and fatalities.
- Culture of safety: A culture of safety is essential for any mine. This means that workers feel comfortable reporting hazards and taking steps to mitigate risks. By creating a culture of safety, mines can help to create a safer working environment for everyone.

7. Conclusion and future outlook

Due to the depletion of shallow ore reserves, underground mines are becoming deeper to access higher-grade mineral resources. The occurrence of fires in deeper underground confined spaces will pose severe hazards. Similarly, the number of tunnels and subways in cities is increasing rapidly. This is due to the growing popularity of public transportation, as well as the need for more efficient transportation networks. However, the increase in the number of tunnels and subways also poses a new fire safety challenge. To address the fire safety challenges, it is important to understand fire characteristics and implement appropriate fire safety measures and emergency evacuation plans.

First, in this study, we analyzed the current advancement in underground mine fire studies by identifying the critical factors such as ventilation conditions, nature of the fuel, geometrical constraints, and simulation methods that could impact fire safety, thus optimizing emergency evacuation plans. Furthermore, the advantages and the defects of the existing mine fire simulation and evacuation planning are presented in which a novel approach to the underground emergency evacuation management system (see Fig. 9) is proposed to help miners self-escape during a fire hazard.

The proposed evacuation model will take into consideration the mine configuration (that is, the geometrical parameters), fire field data (mainly the heat release rate, smoke spread behavior, flame characteristics, and nature of fuel), behavioral rules governing miners' evacuation such as miners' age, sex, education, and experience (which could be obtained from emergency drills like the level 1 emergency drills conducted annually in the State of Queensland) (Halim and Brune, 2019; Queensland-Government, 2022), and finally, the agent population which in this case is the number of miners expected to be underground. This can be achieved by direct coupling of fire dynamics simulation with agent-based evacuation models to form an integrated emergency response system like the Mobilaris Emergency Support.

Current evacuation strategies are based on static evacuation plans. This evacuation method only offers a rigid evacuation path and does not consider changes in the topology of the evacuation network or changes in the evacuation path caused by hazard dynamics. More problematically, just a few locations in the underground mines have evacuation plans, making it difficult for evacuees to access the information from the static evacuation routes.

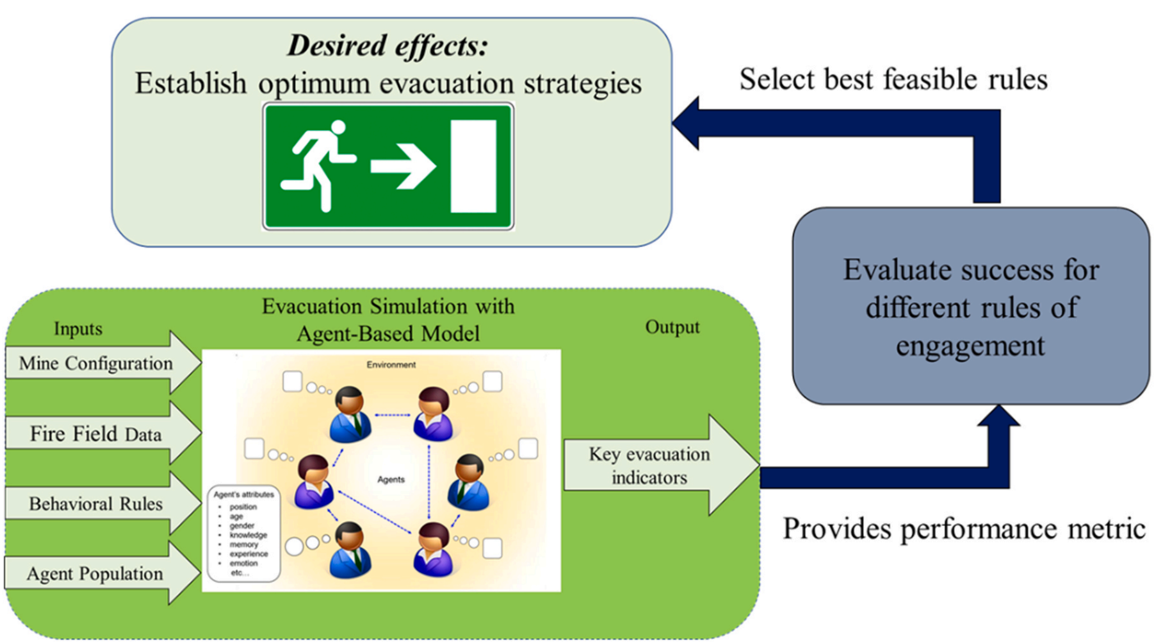

Fig. 9. Proposed structure of Underground Mines evacuation model using ABMs.

To develop reliable self-escape methods for miners during a fire accident, it is imperative to investigate evacuation models by computing the risk factor and the chances of safe escape during an underground fire. This type of model needs to present a complete, comprehensive conceptual model of human behavior in fire evacuations. Agent-based modeling is one reliable way to go, and it has continued to gain worldwide attention and application because of its ability to reliably model numerous complex situations which might be impossible using other conventional modeling tools (Macal and North, 2009).

Although some evident progress has been made in developing safe evacuation models and strategies for buildings, tunnels, and underground facilities, the search for an optimal evacuation procedure for different fire scenarios still presents a challenging task to fire researchers. This is primarily due to the stochastic nature of the input data used for mine fire modeling. For instance, methods for quantification of the efficacy of a model used in another slightly different geometry should be devised. The determination of the probability of safe evacuation for each person in an underground mine based on the selected evacuation strategy must be researched. The method to safely evacuate the miners from the underground immediately after a fire outbreak without first conducting firefighting operations is another proposed research topic. Also, given different evacuation routes from the underground, the measures used to determine the best evacuation route should be studied.

These are some of the drawbacks faced with much of the existing literature trying to model underground mine fire using data obtained from building scaled model tunnels in the laboratory. These issues and many other defects in underground mine fire studies have been addressed in this work thus improving our understanding of fire risk and the required preparedness for emergency evacuation in underground mines and other similar underground confined spaces.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Guang Xu reports financial support was provided by National Institute for Occupational Safety and Health (NIOSH).

Acknowledgements

This research is funded by the National Institute for Occupational Safety and Health (NIOSH) under contract number 75D30120CO8913 and 1 U60OH012350-01-00. The findings and conclusions in this report are those of the authors and do not represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention; nor does mention of trade names, commercial practices, or organizations imply endorsement by the U.S. Government.

References

Adjiski, V., & Despodov, Z. (2020). Methodology for Optimal Fire Evacuations in Underground Mines Based on Simulated Scenarios. In *Fire Safety and Management Awareness*. IntechOpen.

Adjiski, V., Mirakovski, D., Despodov, Z., Mijalkovski, S., 2015. Simulation and optimization of evacuation routes in case of fire in underground mines. J. Sustain. Min. 14 (3), 133–143. https://doi.org/10.1016/j.jsm.2015.10.001.

Adjiski, V., Mirakovski, D., Despodov, Z., Mijalkovski, S., 2016. CFD simulation of the brattice barrier method for approaching underground mine fires. Min. Sci. 23, 161–172.

Al-Waked, R., Nasif, M., Groenhout, N., Partridge, L., 2021. Natural ventilation of residential building Atrium under fire scenario. Case Stud. Therm. Eng. 26, 101041 https://doi.org/10.1016/j.csite.2021.101041.

Babrauskas, V., 1983. Estimating large pool fire burning rates. Fire Technol. 19, 251–261.

Beard, A.N., Jowitt, P., Carvel, R., 1999. The effect of forced longitudinal ventilation on a pool fire in a tunnel. 8th Int Conf. Inter. '99-Fire Sci. Eng.

Binbin, W., 2011. Comparative research on FLUENT and FDS's numerical simulation of smoke spread in subway platform Fire. Procedia Eng. 26, 1065–1075. https://doi.org/10.1016/j.proeng.2011.11.2275.

Bonabeau, E., 2002. Agent-based modeling: methods and techniques for simulating human systems. *Proc. Natl. Acad. Sci.*, *99*(suppl_3) 7280–7287.

Brakea, R., Hattbc, A., & Sanid, R. (2015). Modeling and Simulation of Multiple Underground Mine Fire Scenarios at Freeport Indonesia.

Brnich, M., Kowalski-Trakofler, K.M., Brune, J., 2010. Underground coal mine disasters 1900-2010: events, responses, and a look to the future. Extr. Sci.: a Century Min. Res. 363–372.

Brohez, S., Delvosalle, C., Marlair, G., Tewarson, A., 2000. The measurement of heat release from oxygen consumption in sooty fires. J. fire Sci. 18 (5), 327–353.

Bubbico, R., Dusserre, G., Mazzarotta, B., 2016. Calculation of the flame size from burning liquid pools. Chem. Eng. Trans. 53, 67–72.

Cafaro, E., Bertola, V., 2010. Fires in tunnels: experiments and modelling. Open Thermodyn. J. 4 (1).

Carvel, R., Beard, A.N., Jowitt, P., Drysdale, D., 2001. Variation of heat release rate with forced longitudinal ventilation for vehicle fires in tunnels. Fire Saf. J. 36 (6), 569–596.

Carvel, R.O., Beard, A.N., Jowitt, P., 2001. The influence of longitudinal ventilation systems on fires in tunnels. Tunn. Undergr. Space Technol. 16 (1), 3–21.

Chang, X., Laage, L.W., Greuer, R.E., 1990. A user's manual for MFIRE: a computer simulation program for mine ventilation and fire modeling. In: US Department of the Interior, Vol. 9245. Bureau of Mines.

Chasko, L.L., Conti, R.S., Lazzara, C.P., Wiehagen, W.J., 2005. Fire response preparedness for underground mines. In: Pittsburgh, P.A. (Ed.), Pittsburgh Research Laboratory. (National Institute for Occupational Safety and Health).

Chen, J., Liu, C., Meng, Y., Zhong, M., 2021. Multi-Dimensional evacuation risk evaluation in standard subway station. Saf. Sci. 142, 105392 https://doi.org/10.1016/j.ssci.2021.105392.

Chen, L.F., Hu, L.H., Zhang, X.L., Zhang, X.Z., Zhang, X.C., Yang, L.Z., 2015. Thermal buoyant smoke back-layering flow length in a longitudinal ventilated tunnel with ceiling extraction at difference distance from heat source. Appl. Therm. Eng. 78, 129–135. https://doi.org/10.1016/j.applthermaleng.2014.12.034.

Chen, Y.-J., Shu, C.-M., Ho, S.-P., Kung, H.-C., Chien, S.-W., Ho, H.-H., Hsu, W.-S., 2019. Analysis of smoke movement in the Hsuehshan tunnel fire. Tunn. Undergr. Space Technol. 84, 142–150. https://doi.org/10.1016/j.tust.2018.11.007.

Cheng, J., Li, S., Zhang, F., Zhao, C., Yang, S., Ghosh, A., 2016. CFD modelling of ventilation optimization for improving mine safety in longwall working faces. J. Loss Prev. Process Ind. 40, 285–297.

Cheng, L.H., Ueng, T.H., Liu, C.W., 2001. Simulation of ventilation and fire in the underground facilities. Fire Saf. J. 36 (6), 597–619. https://doi.org/10.1016/S0379-7112(01)00013-3.

Chiew, H.Z. (2013). Fire dynamics simulation (FDS) study of fire in structures with curved geometry [Bachelor thesis, Universiti Tunku Abdul Rahman]. http://eprints.utar.edu.my/818/1/ME-2013–0908547-1.pdf.

Chow, W.K., Han, S., Chow, C., 2008. Estimation of heat release rate for gasoline pool fires. Int. Conf. Build. Energy Environ., Hong. Kong Polytech. Univ.

Chow, W.K., Wong, K.Y., Chung, W.Y., 2010. Longitudinal ventilation for smoke control in a tilted tunnel by scale modeling. Tunn. Undergr. Space Technol. 25 (2), 122–128. https://doi.org/10.1016/j.tust.2009.10.001.

Crooks, A.T., Heppenstall, A.J., 2012. Introduction to Agent-Based Modelling. In: Heppenstall, A.J., Crooks, A.T., See, L.M., Batty, M. (Eds.), Agent-Based Models of Geographical Systems. Springer, Netherlands, pp. 85–105. https://doi.org/10.1007/978-90-481-8927-4_5.

Deckers, X., Haga, S., Tilley, N., Merci, B., 2013. Smoke control in case of fire in a large car park: CFD simulations of full-scale configurations. Fire Saf. J. 57, 22–34. https://doi.org/10.1016/j.firesaf.2012.02.005.

Dent, P., 2002. Developments in mine safety in Queensland, post Moura No. 2 underground coal mine disaster. Qld. Gov. Min. J. *102*.

Dong, B.-X., Shan, M., Hwang, B.-G., 2022. Simulation of transportation infrastructures resilience: a comprehensive review. Environ. Sci. Pollut. Res. 29 (9), 12965–12983. https://doi.org/10.1007/s11356-021-18033-w.

Duy Huy, N., Cao Khai, N., Van Thinh, N., Van Quang, N., Minh Chien, N., Khac Duy, N., 2022. Simulating and predicting escape routes for ventilation network of duong huy coal company using ventsim DESIGN software. Inżynieria Miner.

Edrisi, A., Lahoorpoor, B., Lovreglio, R., 2021. Simulating metro station evacuation using three agent-based exit choice models. Case Stud. Transp. Policy 9 (3), 1261–1272. https://doi.org/10.1016/j.cstp.2021.06.011.

Epiroc (2023). Retrieved Accessed May 22, 2023. from https://www.epiroc.com/en-us/products/digital-solutions/sustainable-and-safe-operations/mobilaris-emergency-support.

Eppstein, D., 1998. Finding the k shortest paths. SIAM J. Comput. *28*. https://doi.org/10.1137/S0097539795290477.

Fan, C., Zhang, L., Jiao, S., Yang, Z., Li, M., Liu, X., 2018. Smoke spread characteristics inside a tunnel with natural ventilation under a strong environmental wind. Tunn. Undergr. Space Technol. 82, 99–110. https://doi.org/10.1016/j.tust.2018.08.004.

Fernández-Alaiz, F., Castañón, A.M., Gómez-Fernández, F., Bernardo-Sánchez, A., Bascompta, M., 2020. Determination and fire analysis of gob characteristics using CFD. Energies 13 (20), 5274.

Fernández-Alaiz, F., Castañón, A.M., Gómez-Fernández, F., Bascompta, M., 2020. Mine fire behavior under different ventilation conditions: Real-scale tests and CFD modeling. Appl. Sci. 10 (10), 3380.

Fernánez-Alaiz, F., Castañón, A.M., Gómez-Fernández, F., Bernardo-Sánchez, A., Bascompta, M., 2020. Analysis of the fire propagation in a sublevel coal mine. Energies 13 (14), 3754.

Gannouni, S., Maad, R.B., 2015. Numerical study of the effect of blockage on critical velocity and backlayering length in longitudinally ventilated tunnel fires. Tunn. Undergr. Space Technol. 48, 147–155. https://doi.org/10.1016/j.tust.2015.03.003.

Gilbert, N., Bankes, S., 2002. Platforms and methods for agent-based modeling. Proc. Natl. Acad. Sci. 7197–7198.

Greuer, R.E. (1977). Study of mine fires and mine ventilation: pt. 1, Computer simulation of ventilation systems under the influence of mine fires.

Gu, D., Zheng, Z., Zhao, P., Xie, L., Xu, Z., Lu, X., 2020. High-efficiency simulation framework to analyze the impact of exhaust air from covid-19 temporary hospitals and its typical applications. Appl. Sci. 10 (11), 3949.

Guo, K., Zhang, L., 2022. Adaptive multi-objective optimization for emergency evacuation at metro stations. Reliab. Eng. Syst. Saf. 219, 108210 https://doi.org/10.1016/j.ress.2021.108210.

Guo, X., Zhang, Q., 2014. Analytical solution, experimental data and CFD simulation for longitudinal tunnel fire ventilation. Tunn. Undergr. Space Technol. 42, 307–313. https://doi.org/10.1016/j.tust.2014.03.011.

Haack, A., 1998. Fire protection in traffic tunnels: general aspects and results of the EUREKA project. Tunn. Undergr. Space Technol. 13 (4), 377–381. https://doi.org/10.1016/S0886-7798(98)00080-7.

Haghighat, A., Gillies, S., 2015. Fire behavior analysis of a mine future plan. 15th North American mine ventilation symposium. Dep. Min. Miner. Eng., Va. Tech., USA.

Haghighat, A., Luxbacher, K., Lattimer, B.Y., 2018. Development of a methodology for interface boundary selection in the multiscale road tunnel fire simulations. Fire Technol. 54 (4), 1029–1066. https://doi.org/10.1007/s10694-018-0724-0.

Haghighat, A. (2017). Fire Simulation Cost Reduction for Improved Safety and Response for Underground Spaces [Doctoral dissertation, Virginia Tech]. https://vtechworks.lib.vt.edu/handle/10919/79672.

Halim, A., Brune, J., 2019. Do refuge chambers represent a good strategy to manage emergencies in underground coal mines? *Mining*. Metall. Explor. 36, 1191–1199.

Han, J., Wang, Z., Geng, P., Wang, F., Wen, J., Liu, F., 2021. The effect of blockage and tunnel slope on smoke spread and ceiling temperature distribution in a natural-ventilated metro depot. Energy Build. 253, 111540 https://doi.org/10.1016/j.enbuild.2021.111540.

Hansen, R., 2019. Fire behaviour of multiple fires in a mine drift with longitudinal ventilation. Int. J. Min. Sci. Technol. 29 (2), 245–254.

Hansen, R., 2020. Modelling temperature distributions and flow conditions of fires in an underground mine drift. Geosystem Eng. 23 (6), 299–314.

Hansen, R., Ingason, H., 2013a. *Full-scale fire experiments with mining vehicles in an underground mine* (978-91-7485-115-1 (ISBN)). (Stud. Sustain. Technol. / Forsk. (Issue) http://urn.kb.se/resolve?urn=urn:nbn:se:mdh:diva-20912.

Hansen, R., Ingason, H., 2013b. Heat release rate measurements of burning mining vehicles in an underground mine. Fire Saf. J. 61, 12–25.

Hansen, R. (2018). Fire statistics from the mining industry in New South Wales, Queensland and Western Australia. Brisbane: The University of Queensland.

Hardy, R.J., Heasley, K.A., 2006. Ventilation simulation programs Mine Vent and MFIRE: updates to advance the technology of simulation programming, 2006 11th US/North American Mine Ventilation Symposium. Pennsylvania, USA.

Hong, Y., Li, D., Wu, Q., Xu, H., 2018. Dynamic route network planning problem for emergency evacuation in restricted-space scenarios. J. Adv. Transp. 2018, 4295419 https://doi.org/10.1155/2018/4295419.

Hong, Y., Li, D., Wu, Q., Xu, H., 2019. Priority-oriented route network planning for evacuation in constrained space scenarios. J. Optim. Theory Appl. 181, 279–297.

Hopkins, A., 2020. Managing major hazards: the lessons of the Moura mine disaster. U. Kingdom:Taylor Fr. ⟨https://www.google.com/books/edition/Managing_Major_Hazards/UMzxDwAAQBAJ?hl=en&gbpv=1⟩.

Hu, Y., Wang, F., Liu, X., 2014. A CPSS approach for emergency evacuation in building fires. IEEE Intell. Syst. 29 (3), 48–52. https://doi.org/10.1109/MIS.2014.38.

Huang, Y., Li, Y., Dong, B., Li, J., Liang, Q., 2018. Numerical investigation on the maximum ceiling temperature and longitudinal decay in a sealing tunnel fire. Tunn. Undergr. Space Technol. 72, 120–130.

Huggett, C., 1980. Estimation of rate of heat release by means of oxygen consumption measurements. Fire Mater. 4 (2), 61–65.

Hwang, C., Edwards, J., 2005. The critical ventilation velocity in tunnel fires—a computer simulation. Fire Saf. J. 40 (3), 213–244.

Ingason, H., Li, Y.Z., 2010a. Model scale tunnel fire tests with longitudinal ventilation. Fire Saf. J. 45 (6–8), 371–384.

Ingason, H., Li, Y.Z., 2010b. Model scale tunnel fire tests with longitudinal ventilation. Fire Saf. J. 45 (6), 371–384. https://doi.org/10.1016/j.firesaf.2010.07.004.

Ingason, H., Wickström, U., 2007. Measuring incident radiant heat flux using the plate thermometer. Fire Saf. J. 42 (2), 161–166. https://doi.org/10.1016/j.firesaf.2006.08.008.

Ingason, H., Li, Y.Z., Lönnermark, A., 2015. Runehamar tunnel fire tests. Fire Saf. J. 71, 134–149. https://doi.org/10.1016/j.firesaf.2014.11.015.

Jahn, W., Rein, G., Torero, J.L., 2008. The effect of model parameters on the simulation of fire dynamics. Fire Saf. Sci. 9, 1341–1352. https://doi.org/10.3801/IAFSS.FSS.9-1341.

Jalali, S.E., Noroozi, M., 2009. Determination of the optimal escape routes of underground mine networks in emergency cases. Saf. Sci. *47*. https://doi.org/10.1016/j.ssci.2009.01.001.

Jin, W., Chen, S., Jiang, H., 2013. Finding the K shortest paths in a time-schedule network with constraints on arcs. Comput. Oper. Res. 40 (12), 2975–2982.

Jinzhang, J., Fengxiao, W., 2022. Study on emergency escape route planning under fire accidents in the Burtai coal mine. Sci. Rep. 12 (1), 13074. https://doi.org/10.1038/s41598-022-15437-7.

Kerber, S., Milke, J.A., 2007. Using FDS to simulate smoke layer interface height in a simple atrium. Fire Technol. 43 (1), 45–75. https://doi.org/10.1007/s10694-007-0007-7.

Khan, M.M., Tewarson, A., Chaos, M., 2016. Combustion characteristics of materials and generation of fire products. In *SFPE handbook of fire protection engineering*. Springer, pp. 1143–1232.

Kong, J., Xu, Z., You, W., Wang, B., Liang, Y., Chen, T., 2021. Study of smoke back-layering length with different longitudinal fire locations in inclined tunnels under natural ventilation. Tunn. Undergr. Space Technol. 107, 103663.

Kong, J., You, W., Xu, Z., Liu, H., Li, H., 2022. A numerical study on smoke behaviors in inclined tunnel fires under natural ventilation. J. Saf. Sci. Resil. 3 (2), 169–178.

KSL.com. (2022, Sept. 23). Retrieved Accesssed May 22, 2023. from https://www.ksl.com/article/50482277/lila-canyon-mine-fire-still-burning-in-carbon-county.

Kuligowski, E.D. (2008). Modeling human behavior during building fires (NIST Technical Note 1619 Issue. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=91d98730af8730f525c678ba12a1fc66121c1993.

Laage, L.W., & Yang, H. (1995, 5–7 Jun). Mine fire experiments and simulation with MFIRE. U.S. mine ventilation symposium, Lexington, KY (United States).

Laage, L.W., & Yang, H. (1991). Mine fire experiments at the Waldo Mine: heat flow. Proceedings of the US Mine Ventilation Symposium, West Virginia University, Morgantown, WV, USA.

Lam, C.S., Weckman, E.J., 2015. Wind-blown pool fire, Part II: comparison of measured flame geometry with semi-empirical correlations. Fire Saf. J. 78, 130–141.

Lee, Y.-P., Tsai, K.-C., 2012. Effect of vehicular blockage on critical ventilation velocity and tunnel fire behavior in longitudinally ventilated tunnels. Fire Saf. J. 53, 35–42. https://doi.org/10.1016/j.firesaf.2012.06.013.

Lemaire, T., Kenyon, Y., 2006. Large scale fire tests in the second benelux tunnel. Fire Technol. 42 (4), 329–350. https://doi.org/10.1007/s10694-006-8434-4.

Li, C., Li, J., Hu, L., Hou, D., 2015. Visualization and simulation model of underground mine fire disaster based on Cellular Automata. Appl. Math. Model. 39 (15), 4351–4364. https://doi.org/10.1016/j.apm.2014.12.051.

Li, Y.Z., Lei, B., Ingason, H., 2010. Study of critical velocity and backlayering length in longitudinally ventilated tunnel fires. Fire Saf. J. 45 (6–8), 361–370.

Li, Y.Z., Lei, B., Ingason, H., 2011. The maximum temperature of buoyancy-driven smoke flow beneath the ceiling in tunnel fires. Fire Saf. J. 46 (4), 204–210. https://doi.org/10.1016/j.firesaf.2011.02.002.

Liang, Y., Zhang, J., Ren, T., Wang, Z., Song, S., 2018. Application of ventilation simulation to spontaneous combustion control in underground coal mine: a case study from Bulianta colliery. Int. J. Min. Sci. Technol. 28 (2), 231–242. https://doi.org/10.1016/j.ijmst.2017.12.005.

Lin, C.-J., Chuah, Y.K., 2008. A study on long tunnel smoke extraction strategies by numerical simulation. Tunn. Undergr. Space Technol. 23 (5), 522–530. https://doi.org/10.1016/j.tust.2007.09.003.

Lönnermark, A., Claesson, A., Lindström, J., Li, Y.Z., Kumm, M., Ingason, H., 2012. Full-scale fire tests with a commuter train in a tunnel. S. T. R. I. o. Swed. ⟨https://www.diva-portal.org/smash/get/diva2:962670/FULLTEXT01.pdf⟩.

Luo, N., Li, A., Gao, R., Zhang, W., Tian, Z., 2013. An experiment and simulation of smoke confinement utilizing an air curtain. Saf. Sci. 59, 10–18. https://doi.org/10.1016/j.ssci.2013.04.009.

Macal, C.M., & North, M.J. (2009, 13–16 Dec. 2009). Agent-based modeling and simulation. Proceedings of the 2009 Winter Simulation Conference (WSC), Austin, TX, USA.

Maragkos, G., Merci, B., 2020. On the use of dynamic turbulence modelling in fire applications. Combust. Flame 216, 9–23. https://doi.org/10.1016/j.combustflame.2020.02.012.

Marková, I., Lauko, J., Makovická Osvaldová, L., Mózer, V., Svetlík, J., Monoši, M., Orinčák, M., 2020. Fire size of gasoline pool fires. Int. J. Environ. Res. Public Health 17 (2), 411.

McGrattan, K., McDermott, R., Floyd, J., Hostikka, S., Forney, G., Baum, H., 2012. Computational fluid dynamics modelling of fire. Int. J. Comput. Fluid Dyn. 26 (6–8), 349–361.

McGrattan, K., Peacock, R., Overholt, K., 2016. Validation of fire models applied to nuclear power plant safety. Fire Technol. 52, 5–24.

McGrattan, K.B., Baum, H.R., Rehm, R.G., 1998. Large eddy simulations of smoke movement. Fire Saf. J. 30 (2), 161–178.

McGrattan, K.B., Peacock, R.D., Overholt, K.J., 2014. Verification and validation of selected fire models for nuclear power plant applications supplement 1. U. S. N. R. C. NUREG 1824. ⟨https://www.nist.gov/publications/verification-and-validation-selected-fire-models-nuclear-power-plant-applications-1⟩.

McGRATTAN, K., 2005. Fire modeling: where are we? where are we going? Fire Saf. Sci. 8, 53–68.

Meng, N., Liu, B., Li, X., Jin, X., Huang, Y., Wang, Q., 2018. Effect of blockage-induced near wake flow on fire properties in a longitudinally ventilated tunnel. Int. J. Therm. Sci. 134, 1–12. https://doi.org/10.1016/j.ijthermalsci.2018.07.037.

Miao, Z., Wenhua, S., Ji, W., Zhen, C., 2014. Accident consequence simulation analysis of pool fire in fire dike. Procedia Eng. 84, 565–577.

Mossberg, A., Nilsson, D., Wahlqvist, J., 2021. Evacuation elevators in an underground metro station: a Virtual Reality evacuation experiment. Fire Saf. J. 120, 103091.

Nematollahi Sarvestani, A., Oreste, P., Gennaro, S., 2023. Fire scenarios inside a room-and-pillar underground quarry using numerical modeling to define emergency plans. Appl. Sci. 13 (7), 4607.

Newman, J.S., 1984. Experimental evaluation of fire-induced stratification. Combust. flame 57 (1), 33–39.

Nguyen, M.H., Ho, T.V., Zucker, J.-D., 2013. Integration of smoke effect and blind evacuation strategy (SEBES) within fire evacuation simulation. Simul. Model. Pract. Theory 36, 44–59.

NIOSH (2021). *Mine Disasters by Accident Type*, 1839–2021 Retrieved Accessed May 22, 2023 from https://wwwn.cdc.gov/NIOSH-Mining/MMWC/MineDisasters/AccidentType.
Oka, Y., Atkinson, G.T., 1995. Control of smoke flow in tunnel fires. Fire Saf. J. 25 (4), 305–322. https://doi.org/10.1016/0379-7112(96)00007-0.
Oka, Y., Kakae, N., Imazeki, O., Inagaki, K., 2013. Temperature property of ceiling jet in an inclined tunnel. Procedia Eng. 62, 234–241.
Onifade, M., 2021. Towards an emergency preparedness for self-rescue from underground coal mines. Process Saf. Environ. Prot. 149, 946–957. https://doi.org/10.1016/j.psep.2021.03.049.
Onifade, M., Genc, B., Said, K., Fourie, M., Akinseye, P., 2022. Overview of mine rescue approaches for underground coal fires: a South African perspective. J. South. Afr. Inst. Min. Metall. 122 (5), 213–226.
Overholt, K.J., 2014. Verification and validation of commonly used empirical correlations for fire scenarios. US Department of Commerce. Natl. Inst. Stand. Technol.
Palacios, A., Rengel, B., Casal, J., Pastor, E., Planas, E., 2020. Computational fluid dynamics modelling of hydrocarbon fires in open environments: literature review. Can. J. Chem. Eng. 98 (11), 2381–2396.
Poulsen, A., Jomaas, G., 2012. Experimental study on the burning behavior of pool fires in rooms with different wall linings. Fire Technol. 48, 419–439.
Queensland-Government. (2022). *Queensland level 1 mine emergency exercise reports* Retrieved Accessed May 22, 2023. from https://www.publications.qld.gov.au/dataset/queensland-level-1-mine-emergency-exercise-reports.
R.S. Conti Fire response preparedness for underground mines U. S. Dep. Health Hum. Serv., Public Health Serv., Cent. Dis. Control Prev., Natl. Inst. Occup. Saf. Health, Pittsburgh Res. Lab. 2005.⟨https://books.google.com/books?id=5-zgAAAAMAAJ⟩.
Rahmani, A., Carlotti, P., Gay, B., Buffat, M., 2004. Simulating fires in tunnels using large eddy simulation. International Conference Tunnel Safety and Ventilation. Graz Conference Proceedings, Graz, Austria.
Railsback, S.F., Grimm, V., 2019. Agent-based and individual-based modeling: a practical introduction. Princeton university press https://www.google.com/books/edition/Agent_Based_and_Individual_Based_Modelin/Zrh2DwAAQBAJ?hl=en&gbpv=0.
Rew, C., Deaves, D., 1999. Fire spread and flame length in ventilated tunnels-a model used in Channel tunnel assessments. Proceedings of the international conference on tunnel fires and escape from tunnels. Lyon, France.
Ronchi, E., Arias, S., La Mendola, S., Johansson, N., 2019. A fire safety assessment approach for evacuation analysis in underground physics research facilities. Fire Saf. J. 108, 102839.
Roxborough, F., 1997. Anatomy of a disaster-the explosion at Moura No 2 coal mine, Australia. Min. Technol. 79 (906), 37–43. ⟨https://www.osti.gov/etdeweb/biblio/453622⟩.
Salarian, A.H., Mashhadizadeh, A., Bagheri, M., 2020. Simulating passenger evacuation in railway station under fire emergency using safe zone approach. Transp. Res. Rec. 2674 (11), 806–812. https://doi.org/10.1177/0361198120950316.
Salvagni, R.G., Centeno, F.R., Indrusiak, M.L.S., 2019. Burning rate, flame geometry and temperature of convection-controlled circular diesel oil pool fire under air crossflow conditions. J. Hazard. Mater. 368, 560–568.
Salvagni, R.G., Indrusiak, M.L.S., Centeno, F.R., 2020. Biodiesel oil pool fire under air crossflow conditions: burning rate, flame geometric parameters and temperatures. Int. J. Heat. Mass Transf. 149, 119164.
Shafee, S., Yozgatligil, A., 2018. An analysis of tunnel fire characteristics under the effects of vehicular blockage and tunnel inclination. Tunn. Undergr. Space Technol. 79, 274–285. https://doi.org/10.1016/j.tust.2018.05.019.
Shen, T.-S., 2005. ESM: a building evacuation simulation model. Build. Environ. 40 (5), 671–680. https://doi.org/10.1016/j.buildenv.2004.08.029.
Singh, C.S., Bhattacharjee, R., Agrawal, H., 2021. An investigation on emergency response system during Anjan hill coal mine disaster using control task analysis–a cognitive approach. J. Mines, Met. Fuels 445–454.
Smith, A.C., Thimons, E.D., 2009. A summary of US mine fire research. SME annual meeting and exhibit. Denver, Colorado.
Steinhaus, T., Welch, S., Carvel, R.O., Torero, J.L., 2007. Large-scale pool fires. Therm. Sci. 11 (2), 101–118.
Stewart, C., 2021. Challenges and solutions in the development of the VentFIRE mine network fire simulator. In *Mine Ventilation*. CRC Press, pp. 300–308.
Stewart, C., Aminossadati, S., Kizil, M., 2015. Underground fire rollback simulation in large scale ventilation models. 15th North Am. Mine Vent. Symp.
Tan, L., Hu, M., Lin, H., 2015. Agent-based simulation of building evacuation: Combining human behavior with predictable spatial accessibility in a fire emergency. Inf. Sci. 295, 53–66.
Tang, F., Ren, A., 2008. Agent-based evacuation model incorporating fire scene and building geometry. Tsinghua Sci. Technol. 13 (5), 708–714. https://doi.org/10.1016/S1007-0214(08)70115-9.
Tang, F.Q., Ren, A., 2012. GIS-based 3D evacuation simulation for indoor fire. Build. Environ. *49*. https://doi.org/10.1016/j.buildenv.2011.09.021.
Tang, W., Yuan, L., Bahrami, D., Rowland, J., 2021. Water spray suppression of leaked oil fires: a numerical study. In *Mine Ventilation*. CRC Press, pp. 309–316.
Tewarson, A., 1980. Heat release rate in fires. Fire Mater. 4 (4), 185–191.
Thomas, P.H., 1963. The size of flames from natural fires. Symposium (International) on Combustion. Elsevier.
Tilley, N., Rauwoens, P., Merci, B., 2011. Verification of the accuracy of CFD simulations in small-scale tunnel and atrium fire configurations. Fire Saf. J. 46 (4), 186–193. https://doi.org/10.1016/j.firesaf.2011.01.007.
Trevits, M.A., Yuan, L., Teacoach, K., Valoski, M., Urosek, J., 2009. Understanding mine fires by determining the characteristics of deep-seated fires. SME Annu. Meet., Denver, Colo.
Trouvé, A., Wang, Y., 2010. Large eddy simulation of compartment fires. Int. J. Comput. Fluid Dyn. 24 (10), 449–466.
Tsai, K.-C., Chen, H.-H., Lee, S.-K., 2010. Critical ventilation velocity for multi-source tunnel fires. J. Wind Eng. Ind. Aerodyn. 98 (10), 650–660. https://doi.org/10.1016/j.jweia.2010.06.006.
Van Maele, K., Merci, B., 2008. Application of RANS and LES field simulations to predict the critical ventilation velocity in longitudinally ventilated horizontal tunnels. Fire Saf. J. 43 (8), 598–609. https://doi.org/10.1016/j.firesaf.2008.02.002.
Vasanth, S., Tauseef, S.M., Abbasi, T., Abbasi, S.A., 2013. Assessment of four turbulence models in simulation of large-scale pool fires in the presence of wind using computational fluid dynamics (CFD. J. Loss Prev. Process Ind. 26 (6), 1071–1084. https://doi.org/10.1016/j.jlp.2013.04.001.
Verda, V., Borchiellini, R., Cosentino, S., Guelpa, E., Tuni, J.M., 2021. Expanding the FDS simulation capabilities to fire tunnel scenarios through a novel multi-scale model. Fire Technol. 57 (5), 2491–2514. https://doi.org/10.1007/s10694-020-01081-y.
Vermesi, I., Rein, G., Colella, F., Valkvist, M., Jomaas, G., 2017. Reducing the computational requirements for simulating tunnel fires by combining multiscale modelling and multiple processor calculation. Tunn. Undergr. Space Technol. 64, 146–153. https://doi.org/10.1016/j.tust.2016.12.016.
Wan, H., Gao, Z., Han, J., Ji, J., Ye, M., Zhang, Y., 2019. A numerical study on smoke back-layering length and inlet air velocity of fires in an inclined tunnel under natural ventilation with a vertical shaft. Int. J. Therm. Sci. 138, 293–303.
Wang, J., Yuan, J., Fang, Z., Tang, Z., Qian, P., Ye, J., 2018. A model for predicting smoke back-layering length in tunnel fires with the combination of longitudinal ventilation and point extraction ventilation in the roof. Tunn. Undergr. Space Technol. 80, 16–25.
Wang, N., Gao, Y., Li, C.-y., & Gai, W.-m. (2021). Integrated agent-based simulation and evacuation risk-assessment model for underground building fire: A case study. Journal of Building Engineering, 40, 102609.
Wei, F., Fangping, Z., Huiqing, L., 2011. The use of 3D simulation system in mine ventilation management. Procedia Eng. 26, 1370–1379. https://doi.org/10.1016/j.proeng.2011.11.2313.
Weng, M.-c, Lu, X.-l, Liu, F., Shi, X.-p, Yu, L.-x, 2015. Prediction of backlayering length and critical velocity in metro tunnel fires. Tunn. Undergr. Space Technol. 47, 64–72. https://doi.org/10.1016/j.tust.2014.12.010.
Woodburn, P., Britter, R., 1996. CFD simulations of a tunnel fire—part II. Fire Saf. J. 26 (1), 63–90.
Wu, F., Zhou, R., Shen, G., Jiang, J., Li, K., 2018. Effects of ambient pressure on smoke back-layering in subway tunnel fires. Tunn. Undergr. Space Technol. 79, 134–142. https://doi.org/10.1016/j.tust.2018.05.011.
Xiang, Z., Si, G., Wang, Y., Belle, B., Webb, D., 2021. Goaf gas drainage and its impact on coal oxidation behaviour: a conceptual model. Int. J. Coal Geol. 248, 103878 https://doi.org/10.1016/j.coal.2021.103878.
Yi, L., Niu, J.L., Xu, Z.S., Wu, D.X., 2013. Experimental studies on smoke movement in a model tunnel with longitudinal ventilation. Tunn. Undergr. Space Technol. 35, 135–141. https://doi.org/10.1016/j.tust.2013.01.005.
Yu, L.-X., Beji, T., Zadeh, S.E., Liu, F., Merci, B., 2016. Simulations of Smoke Flow Fields in a Wind Tunnel Under the Effect of an Air Curtain for Smoke Confinement. Fire Technol. 52 (6), 2007–2026. https://doi.org/10.1007/s10694-016-0598-y.
Yuan, J.-P., Fang, Z., Yin, Z.-C., Lo, S.-M., 2009. Combined network model for occupant evacuation in building fires [22_Publication in policy or professional journal]. Tumu Jianzhu yu Huanjing Gongcheng/J. Civil Archit. Environ. Eng. 31 (2). ⟨http://www.scopus.com/inward/record.url?scp=66149096626&partnerID=8YFLogxK⟩.
Yuan, L., Smith, A.C., 2009. CFD modeling of spontaneous heating in a large-scale coal chamber. J. Loss Prev. Process Ind. 22 (4), 426–433. https://doi.org/10.1016/j.jlp.2009.02.016.
Yuan, L., Smith, A.C., 2015. Numerical modeling of water spray suppression of conveyor belt fires in a large-scale tunnel. Process Saf. Environ. Prot. 95, 93–101. https://doi.org/10.1016/j.psep.2015.02.018.
Yuan, L., Zhou, L., Smith, A.C., 2016. Modeling carbon monoxide spread in underground mine fires. Appl. Therm. Eng. 100, 1319–1326. https://doi.org/10.1016/j.applthermaleng.2016.03.007.
Zanzi, C., Gómez, P., López, J., Hernández, J., 2019. Analysis of heat and smoke propagation and oscillatory flow through ceiling vents in a large-scale compartment fire. Appl. Sci. 9 (16).
Zhai, Z.J., Zhang, Z., Zhang, W., Chen, Q.Y., 2007. Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: part 1—summary of prevalent turbulence models. HVACR Res. 13 (6), 853–870. https://doi.org/10.1080/10789669.2007.10391459.
Zhang, G., Zhu, G., Yuan, G., Wang, Y., 2016. Quantitative risk assessment methods of evacuation safety for collapse of large steel structure gymnasium caused by localized fire. Saf. Sci. 87, 234–242. https://doi.org/10.1016/j.ssci.2016.04.013.
Zhang, X. (2012). Underground mine fire simulation using multiscale modeling approach [Doctoral dissertation, Missouri University of Science and Technology.]. https://www.proquest.com/docview/1322967711?pq-origsite=gscholar&fromopenview=true.
Zhang, X., Lin, Y., Shi, C., Zhang, J., 2021. Numerical simulation on the maximum temperature and smoke back-layering length in a tilted tunnel under natural ventilation. Tunn. Undergr. Space Technol. 107, 103661 https://doi.org/10.1016/j.tust.2020.103661.
Zhang, Z., Zhang, W., Zhai, Z.J., Chen, Q.Y., 2007. Evaluation of various turbulence models in predicting airflow and turbulence in enclosed environments by CFD: part 2—comparison with experimental data from literature. HVACR Res. 13 (6), 871–886. https://doi.org/10.1080/10789669.2007.10391460.
Zhen, C., Xiaolin, W., 2014. Analysis for combustion properties of crude oil pool fire. Procedia Eng. 84, 514–523. https://doi.org/10.1016/j.proeng.2014.10.463.

Zheng, S., Liu, H., 2019. Improved multi-agent deep deterministic policy gradient for path planning-based crowd simulation. IEEE Access 7, 147755–147770. https://doi.org/10.1109/ACCESS.2019.2946659.

Zhiyin, Y., 2015. Large-eddy simulation: past, present and the future. Chin. J. Aeronaut. 28 (1), 11–24. https://doi.org/10.1016/j.cja.2014.12.007.

Zhou, L., Smith, A.C., 2012. Improvement of a mine fire simulation program—incorporation of smoke rollback into MFIRE 3.0. J. fire Sci. 30 (1), 29–39.

Zhou, L., Smith, A., Yuan, L., 2016. New improvements to MFIRE to enhance fire modeling capabilities. Min. Eng. 68 (6), 45.

Zhou, L., Yuan, L., Bahrami, D., Thomas, R.A., Rowland, J.H., 2018. Numerical and experimental investigation of carbon monoxide spread in underground mine fires. J. Fire Sci. 36 (5), 406–418. https://doi.org/10.1177/0734904118793891.

Zhou, L., Yuan, L., Thomas, R., Bahrami, D., Rowland, J., 2020. An improved method to calculate the heat release rate of a mine fire in underground mines. Mining Metall. Explor. 37 (6), 1941–1949.

, 2009Zhou, L. (2009). Improvement of the mine fire simulation program MFIRE [Doctoral dissertation West Virginia University]. https://researchrepository.wvu.edu/etd/2937.

Zhu, Y., Wang, D., Shao, Z., Xu, C., Zhu, X., Qi, X., Liu, F., 2019. A statistical analysis of coalmine fires and explosions in China. Process Saf. Environ. Prot. 121, 357–366. https://doi.org/10.1016/j.psep.2018.11.013.