Journal of Mines, Metals and Fuels, *72(6): 541-555; 2024. DOI: 10.18311/jmmf/2024/44846*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.com/index.php/jmmf*

Mining Safety Through Artificial Intelligence: A Survey

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Abstract

The challenges workers face in underground mines are numerous and hazardous, with potential threats to their safety and well-being. Mining accidents are caused by various factors, including hardware errors and environmental deficiencies. In response to these hazards, the mining industry has made significant efforts to improve safety through the implementation of advanced technologies. Artificial Intelligence (AI) technology has been notably integrated into mine ventilation systems in recent years. A ventilation network in a mine is a sophisticated system with many interdependent processes, some of which present difficulties for deterministic simulation techniques. This paper aims to discuss major hazards caused by ventilation and provide an overview of various AI advances in mine ventilation to monitor various environmental parameters such as gas concentrations and heat.

Keywords: *Artificial Intelligence, Mine Ventilation, Monitoring Systems, Underground Mine Hazards, Workers Safety*

1.0 Introduction

The increasing mechanisation and stringent safety regulations in underground mining operations have heightened the need for optimising mine ventilation systems[1]. Ventilation plays a critical role in ensuring the safety and well-being of the workers by providing sufficient air quality and quantity in all active areas of the mine. Recent research has explored the use of advanced techniques, such as 3D simulation and mathematical modelling, to design and optimise primary mine ventilation systems.

Underground ventilation is a crucial aspect of mine safety and productivity. When mining operations are functioning underground, mine ventilation is required to provide fresh air and remove air contaminated with toxic gases to minimise the risk of mine fires and to provide breathable air for miners. Ventilation also stabilises the underground atmosphere, preventing gases from being released accidentally through interconnectivity between mine areas. Therefore, good mine ventilation is essential for mine safety and a continuous supply of fresh air from the surface must be ensured to remove toxic gases. In addition to providing clean air for the miners, ventilation serves to control temperature and humidity to ensure worker comfort. Furthermore, underground diesel engines contribute significantly to the input of gases into shafts and tunnels, which can create difficulties in terms of health and safety, environment, and ventilation in mines. According to the National Institute for Occupational

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Safety and Health (NIOSH), mine ventilation costs are one of the largest operating expenses in a mine.

A key challenge in underground mine ventilation is managing complex airflow networks, particularly in cases where the geology and mining layout create intricate airway paths[2]. Solving these complex ventilation networks using computational methods allows for the modelling and simulation of potential changes to the ventilation system, enabling operators to optimise air management and visualise network dynamics in real-time[3].

Researchers have developed various software tools that leverage Geographic Information Systems (GIS) and Computational Fluid Dynamics (CFD) to model and analyse mine ventilation systems. These integrated software packages, such as Ventsim, MFire, and CIMVCM, allow mine operators to assess ventilation requirements, model airflow patterns and identify opportunities for improving efficiency and safety.

Through the application of such computational tools, mine operators can optimise the number, placement and performance of ventilation fans and regulators to distribute the required fresh airflow at minimum cost while maintaining safe working conditions for underground personnel.

AI and machine learning techniques have also emerged as promising approaches for enhancing mine ventilation management. These data-driven methods can be used to predict air quality trends, identify potential hazards, and automatically adjust ventilation parameters in response to changing operating conditions [2,4–6].

Integrating AI-based control systems with sensor networks in underground mines can enable real-time monitoring and adaptive ventilation management, leading to improved worker safety, reduced energy consumption, and more efficient overall operations[2,7,8].

In recent years, there has been a growing interest in utilising AI to enhance workers' safety in underground mines, particularly when it comes to ventilation. AI systems can learn from past experiences or outcomes and make decisions based on these experiences[9]. By analysing historical data on air quality and ventilation systems, AI can identify patterns and make predictions about potential hazards or inefficiencies in underground mines. These predictions can then be used to optimise ventilation strategies, ensuring that workers have access to clean and safe air at all times. Furthermore, AI can also assist in real-time monitoring and control of ventilation systems. By continuously monitoring air quality parameters such as temperature, humidity, gas levels and air flow rates, AI algorithms can detect anomalies or deviations from the desired standards and alert workers or operators for immediate action[10]. This can significantly reduce the risk of dangerous conditions such as important levels of toxic gases or inadequate air circulation. Additionally, AI can also help in the early detection of ventilation system malfunctions or failures[11]. By analysing sensor data from various components of the ventilation system, AI algorithms can automatically detect any deviations from normal operating conditions and alert maintenance teams for timely repairs[1,12–14].

1.1 Importance of Adequate Ventilation

Underground mines present several health and safety risks, including ground instability, toxic exposure, sudden gas discharges and an insufficient supply of oxygen. Stores of compressed air and air scrubbers can help miners breathe. However, without adequate ventilation, there is a risk of asphyxiation leading to hypothermia or heat stroke. Fire and explosions are also significant concerns in underground mines due to flammable gases and highly combustible dust. Inadequate ventilation increases the likelihood of a fire explosion due to counteracting the reduction of gas, the decrease in temperature, and the depletion of oxygen. Researchers have long been using AI to optimise the quality and flow of air in underground mines.

1.2 Challenges in Underground Ventilation

The challenges associated with underground mine ventilation are multifaceted and complex, requiring a comprehensive understanding of the intricate balance between air supply, air quality and operational efficiency.

One of the primary challenges is the need to constantly supply fresh air to the mine to effectively disperse gaseous pollutants and control the concentration of airborne particulates[2]. This task is complicated by the dynamic and ever-changing nature of underground mine workings, where new development and production activities constantly alter the ventilation requirements.

The ventilation system is also a crucial consideration, as the electricity consumption associated with ventilation

can account for a massive portion of the total energy costs in a mine. Consequently, the design and optimisation of the ventilation system must balance the need for adequate airflow with the imperative for energy efficiency. The complexity of underground mine ventilation is further compounded by the presence of challenging geological conditions, such as the mining of bauxite deposits, where the development of new access works must often navigate through existing lenses and clusters of ore bodies. In such cases, a clean and straightforward ventilation network is rarely achievable, necessitating the development of sophisticated modelling and optimisation techniques to ensure the efficacy of the ventilation system.

Optimising the ventilation system is crucial, as it directly affects the well-being of mine workers. With increasingly strict regulatory requirements for air quality, a rational and efficient ventilation system has become even more essential.

Ventilation management programs, as described in[5], can be a valuable tool in addressing these challenges, as they enable compliance with regulations, enhance safety, improve operational efficiency and reduce operating costs.

2.0 Lack of Ventilation: Impact on Workers

2.1 Heat stress

Workers in underground mines face various risks due to the nature of their work environment. Underground mines can be hot and humid due to the lack of ventilation and the presence of machinery. Heat stress can be a significant risk for workers in such environments (Figure 1).

The international ergonomic norm ISO 9886:2004 prescribes methods for measuring physiological parameters such as body core temperature, skin temperature, heart rate and body mass loss.

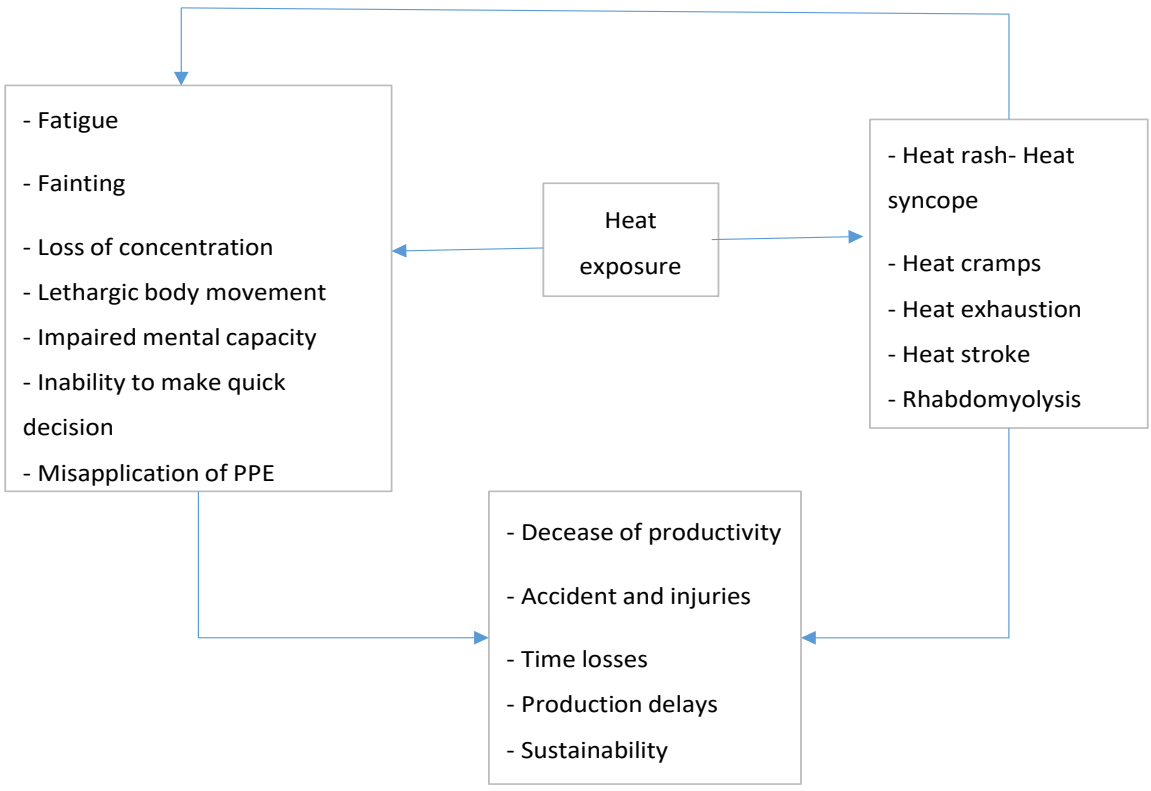


Figure 1. Effects of heat stress over time[17].

According to ISO 7243, the given definition of "heat stress" is "A person exposed to a hot environment is subjected to heat stress, in particular, is dependent upon the production of heat inside the body as a result of physical activity and the characteristics of the environment governing heat transfer between the atmosphere and the body". The heat stress index joins the impacts of six essential factors in any individual's thermal surroundings. So that its value changes depending on how much thermal stress a person is experiencing[15].

The degree to which the body adapts to heat stress relies on several individual parameters, including age, gender, obesity level, acclimatisation behaviour and sensitivity[16].

The challenging environment faced by underground mine workers, particularly the intense heat and humidity, poses significant risks to their health and well-being. Heat-related illnesses, such as heat exhaustion and heat stroke, are common occupational hazards in these settings[18]. Evaluating the factors that contribute to heat strain, including job tasks, physical characteristics, and work shifts, is crucial for developing effective strategies to protect this vulnerable population.

Research has shown that underground mine workers are at a substantial risk of heat-related illnesses due to the nature of their work environment[19]. Factors such as heavy physical exertion, limited airflow and the use of personal protective equipment can exacerbate the effects of heat and humidity on the body. Additionally, the long work shifts and lack of adequate rest periods further contribute to the risk of heat strain among these workers.

To address these challenges, it is important to implement preventive measures such as providing adequate hydration, regular rest breaks in shaded or air-conditioned areas and proper acclimatisation programs for new workers. Furthermore, developing and enforcing heat stress management protocols can significantly reduce the incidence of heat-related illnesses and ensure the health and safety of underground mine workers.

Understanding the impact of heat on underground mine workers is crucial for implementing effective interventions and safeguarding the well-being of this workforce. In the following sections, we will delve into the specific factors contributing to heat strain and explore strategies for mitigating its effects.

The environmental conditions in underground mines, such as elevated temperatures, humidity, and lack of airflow, can contribute to significant heat strain on workers[20]. The release of heat from the surrounding rock, as well as the heat generated by mining equipment and the workers themselves, can further exacerbate the thermal stress[21].

In addition to the environmental factors, the physical characteristics of the workers, such as body composition, age and fitness level, can also influence their susceptibility to heat strain. Miners with higher Body Mass Index (BMI) tend to have lower core body temperatures, which may be attributed to their greater heat storage capacity. Furthermore, shift work, which is common in underground mining operations, has been shown to affect the body's thermoregulatory responses, with night shift workers experiencing lower core body temperatures.

To mitigate the effects of heat strain on underground mine workers, a multi-faceted approach is crucial. Providing adequate hydration is essential and this can be achieved through strategically located water stations throughout the mine and regular reminders for workers to drink water. Additionally, promoting the consumption of electrolyte-rich beverages can help replenish the body's lost minerals due to sweating[22].

Exposure to extreme heat in underground mines can lead to a range of heat-related illnesses, including heat exhaustion and heat stroke. Heat exhaustion is characterised by symptoms such as fatigue, dizziness, headache and nausea, and if left untreated, can progress to the more severe condition of heat stroke[19,23,24].

Heat stroke is a life-threatening emergency, where the body's temperature regulation system fails and the core body temperature rises to dangerously high levels. This can result in organ damage, seizures and even death if not addressed promptly[25].

The physiological effects of heat stress can also lead to reduced physical and mental performance, as the body directs its resources to maintain core temperature and hydration. This can increase the risk of accidents and injuries, further jeopardising the safety and well-being of underground mine workers[20,26,27].

The underground mining environment presents a unique set of challenges when it comes to worker safety and well-being and one of the most pressing concerns in this context is the issue of heat stress. Heat is an integral part of mining activities, and various conditions in the underground environment can contribute to its accumulation, leading to a hazardous situation for

Table 1. Heat illnesses and their associated symptoms[29]

Disorder	Symptoms
Heat stroke	Confusion, Altered Mental Status, Slurred Speech Loss of Consciousness (Coma) Hot, dry skin or profuse sweating, Seizures, Very high body temperature Fatal if treatment is delayed.
Heat exhaustion	Headache Nausea Dizziness Weakness Irritability Thirst Heavy Sweating Elevated Body Temperature Decreased Urine Output
Heat cramps	Muscle cramps, pain, or spasms in the abdomen, arms, or legs.
Heat rashes	Red clusters of pimples or small blisters usually appearing on the neck, upper chest, groin, under the breasts and in elbow creases.
Rhabdomyolysis	Muscle cramps/pain abnormally dark (tea or cola-colored) urine, weakness, exercise intolerance and asymptomatic.
Heat syncope	Fainting (short duration), dizziness and light-headedness from standing too long or suddenly rising from a sitting or lying position

workers. Effective strategies for assessing and mitigating heat stress are crucial for ensuring the safety, health and productivity of underground miners.

One of the key factors contributing to heat stress in underground mines is the release of heat from the surrounding rock formations[16]. The depth of the mine and the insulating properties of the rock can trap this heat, leading to elevated temperatures within the work environment. Additionally, the use of machinery and equipment, as well as the physical exertion of the miners themselves, can all contribute to the buildup of heat within the confined underground spaces. Proper ventilation systems are essential for removing this excess heat and maintaining a safe and comfortable working environment for the miners[28]. The consequences of exposure to heat and humidity have a growing impact on the health and safety of mine workers. Table 1 summarises the heat illnesses and their associated symptoms.

The issue of heat management in underground mines is a critical concern that has long been the focus of extensive research and regulatory efforts. Underground mining activities generate significant amounts of heat from various sources, including the surrounding rock, equipment operation and compressed airflow. As mines delve deeper into the earth, the rising rock pressure and virgin rock temperature can have adverse effects on the working environment, leading to increased costs for effective thermal management[30].

Traditionally, air ventilation alone has often proven insufficient in removing the generated heat, necessitating the addition of air conditioning systems[30]. Researchers have explored various thermal management strategies, including the use of surrounding rocks or abandoned mine voids for thermal storage and regulation[31]. Another approach involves the strategic placement of water-source heat pumps to extract heat from the mine water

Table 2. Temperature limits for underground work

Workload	ACGIH	AIHA	OSHA	ISO	NIOSH
Resting		32.2 °C (90 °F) 100 kcal/h (117W)		33 °C (91.4 °F) <100 kcal/h (117W)	
Light	30 °C (86 °F) 100-200 kcal/h (117-233 W)	30 °C (86 °F) 200 kcal/h (233 W)	30.0 °C (86 °F) - 32.2 °C (90 °F) <200 kcal/h (233 W)	30 °C (86 °F) 100-201 kcal/h (117-234 W)	30 °C (86 °F) <200 kcal/h (233 W)
Moderate	26.7 °C (80 °F) 201-350 kcal/h (234-407 W)	26.7 °C (80 °F) 300 kcal/h (349 W)	27.8 °C (82 °F) - 30.6 °C (87.1 °F) 201-300 kcal/h (234-349 W)	28 °C (82.4 °F) 201-310 kcal/h (234-360 W)	28 °C (82.4 °F) 201-300 kcal/h (234-349 W)
Heavy			26.1 °C (79 °F) - 28.9 °C (84 °F) >301 kcal/h (350 W)	25 °C (77 °F) – 36 °C (78.8 °F) 310-403 kcal/h (360-468 W)	26 °C (78.8 °F) 301-400 kcal/h (350-465 W)
Very Heavy	25 °C (77 °F) 350-500 kcal/h (407-581 W)			23 °C (73.4 °F) – 25 °C (77°F) >403 kcal/h (468 W)	25 °C (77 °F) 401-500 kcal/h (466-580 W)

and alleviate the high-temperature and high-humidity conditions[32].

In terms of regulatory oversight, governing bodies such as the Occupational Safety and Health Administration in the United States have established heat exposure limits and guidelines to protect the health and safety of miners. These regulations on Table 2 often specify maximum allowable skin temperatures, air velocities and other environmental parameters to ensure that miners can work safely and comfortably during their shifts.

The challenge of maintaining acceptable thermal conditions in underground mines remains an ongoing concern, requiring a multifaceted approach that combines innovative engineering solutions, rigorous monitoring and effective regulatory oversight[26].

2.2 Asphyxia

Asphyxia, a life-threatening condition characterised by a lack of oxygen supply, poses a significant risk to workers in underground mines, where the environment can be particularly hazardous. The safety of mine workers depends on a variety of factors, including knowledge of dynamic environments, capability to recognise hazards and react appropriately, training, experience and effective communication.

Effective emergency preparedness and response are critical to reducing the risk of asphyxia in underground mines[33]. Responsible persons should be trained to conduct and assign several duties during an emergency, such as fires, explosions and gas or water inundations[33]. The planning and training of such emergencies is the key element that increases the probability of survival[34]. Research has shown that the initial moments of a mine emergency can be crucial to the outcome. Miners must be able to recognise and respond to the signs of asphyxia promptly, as delayed action can have devastating consequences. Similarly, the use of technology, such as laser lights and lifelines, can significantly improve the chances of survival by guiding personnel to safety in smoke-filled environments. Additionally, conducting regular evacuation drills, even in smoke-free environments can help miners become more familiar with the process and

Table 3. Exposure limits for gaseous pollutants from diesel engines

Gas	ACGIH	OSHA	NIOSH	MSHA coal	MSHA MNM	EU	Australia
CO_2	0.5% TWA 3.0% STEL	0.5% TWA	0.5% TWA 3.0% STEL	0.5% TWA 3.0% STEL	0.5% TWA 1.5% STEL	N/A	0.5% TWA 3.0% STEL
CO	25 ppm TWA	50 ppm TWA	35 ppm TWA 200 ppm C	50 ppm TWA 400 ppm C	50 ppm TWA 400 ppm C	20 ppm TWA 100 ppm STEL	30 ppm TWA
NO	25 ppm TWA	25 ppm TWA	25 ppm TWA	25 ppm TWA	25 ppm TWA 37.5 ppm STEL	2 ppm TWA	25 ppm TWA
NO_2	0.2 ppm TWA 1 ppm STEL	1 ppm STEL	1 ppm STEL	5 ppm C	5 ppm C	0.5 ppm TWA 1 ppm STEL	3 ppm TWA 5 ppm STEL
DPM	20 µg/m^3 EC	N/A	160 µg/m^3 TC	2.5 g/hr of DPM for both permissible and non-permissible equipment	160 µg/m^3 TC	50 µg/m^3 EC	100 µg/m3 EC

improve their ability to respond effectively during real emergencies[35].

The safety of mine workers is paramount and continuous efforts to improve emergency preparedness and response are essential to reducing the risk of asphyxia in underground mines.

Regulations and standards are essential for maintaining safety in underground mines. The mining industry has adopted various regulatory frameworks and policies to address the unique challenges faced in underground operations. To prevent asphyxia, exposure limits must be considered as shown below in Table 3.

3.0 Advantages of AI in Ventilation Monitoring

Even with the benefits of AI, certain challenges have to be worked out for the deployment and application. AI demands a large amount of energy, so the final AI deployment should consider the kind of resources, such as the need for a robust sensor network. Furthermore, another risk related to AI is the adoption by various users, with no or incorrect knowledge related to the decisions based on the AI models, because this fact can induce conflicts with all stakeholders of the mining organization. Experience and knowledge, including data used to train neural networks, alongside stakeholders, have to be transparent and detailed and provide clear interpretation so the knowledge generated by the models can be associated with the current context.

AI offers several benefits for monitoring underground mine ventilation. Considering that there is a limited number of operational data from underground mines, AI only needs a small amount of data to find the necessary pattern or model. AI is better at evaluating big data sets than humans. It can employ data from several sources of diverse complicated aspects for learning, including data from unconventional sensors or data that miners or basic techniques do not take into consideration. Moreover, real-time input and output monitoring is made possible by the application of pattern recognition algorithms, which allows strategy adjustments in response to modifications in the environment or regulations. This facilitates quicker, in-the-moment decision-making for enhanced operational safety.

Research on worker safety is crucial and many efforts in sophisticated data processing are concentrated on the problems of real-time analysis. It is possible to increase productivity and safety in underground mines by implementing intelligent ventilation systems.

Developments in ZigBee and other Wireless Sensor Network (WSN) technologies have paved the way for the creation of real-time monitoring and control systems that can adapt ventilation to changing conditions. To guarantee a safe working environment for miners, these AI-powered ventilation systems can automatically change ventilation as needed, detect harmful chemicals, and continuously check air quality. Furthermore, enormous volumes of data can be analysed by AI algorithms to forecast future ventilation or air quality issues, enabling proactive maintenance and intervention.

4.0 Advances in Mine Safety AI Ventilation

The integration of AI with ventilation systems in underground mines has been the focus of several research studies[36]. Researchers have developed dynamic models and early warning systems that combine real-time sensor data Table 4, ventilation models and machine learning algorithms to detect and mitigate safety hazards.

For example, one study proposed an intelligent safety monitoring robot for coal mine shaft construction that can integrate data and information from various systems, including the ventilation system, to provide comprehensive safety monitoring and hazard recognition[37]. Another study explored the use of an Internet of Things (IoT)-based smart helmet that can detect hazards such as toxic gas accumulation and trigger alerts to workers[12]. Similarly, researchers have also investigated the use of ventilation optimisation techniques that leverage IoT and data analytics to adjust airflow in response to changing mining activities and environmental conditions[12,13].

The integration of historical and real-time sensor data through predictive modelling plays a crucial role in the early detection of environmental changes and potential safety concerns in underground mines:

1. **Data-Driven Insights**: By combining historical data with real-time sensor readings, predictive models can identify normal variations versus abnormal patterns that could signal the onset of unsafe conditions.
2. **Trend Analysis**: Historical data allows the AI system to learn from past events and conditions, understanding trends and correlations that may not be immediately obvious to human operators. These trends are used to inform the understanding of real-time sensor data.
3. **Anomaly Detection**: Predictive models are adept at detecting anomalies that deviate from historical patterns. For example, a sudden increase in toxic gas levels or a drop in oxygen that deviates from past data can trigger alerts.
4. **Environmental Forecasting**: The models can forecast the environmental conditions within the mine, such as predicting the spread of hazardous gases based on ventilation flow, workforce locations, and previous gas release events, enabling pre-emptive action to avert potential risks.
5. **Continuous Learning**: Over time, the models refine their predictive accuracy by learning from new data. This iterative process means that the system becomes more adept at forecasting and detecting potential issues as more data is collected.
6. **Initiative-Taking Management**: With predictive modelling, mine operators can shift from a reactive to a proactive posture in managing environmental risks. Instead of waiting for thresholds to be exceeded, they can anticipate changes and intervene earlier.
7. **Integrated Response**: The integration of predictive modelling with mine operation systems allows for an automated or semi-automated response to potential safety concerns, such as adjusting ventilation flow or evacuating personnel from high-risk areas.

Overall, the application of AI in underground mine ventilation has significant potential to enhance workers' safety and improve the overall efficiency of the ventilation system, as shown in Table 4. By integrating AI-based monitoring, prediction and control capabilities, mining companies can reduce the risk of ventilation-related incidents and ensure a safe working environment for their employees.

Real-time monitoring in mine ventilation systems is addressed through various AI and machine learning techniques. For instance, an intelligent mine ventilation system should utilise full real-time monitoring data[4] integrated GIS and a transient ventilation network model to support real-time decision-making, envisioning an intelligent mine ventilation system. Additionally[44] introduced a method for remote intelligent air control

Table 4. Different sensors used in monitoring underground ventilation[38-43]

Applications	Monitored parameters	Sensor Type
Environment Monitoring	Gas Concentration (NOx, CH_4, CO, CO_2, O_2, etc), Temperature, Airflow Quantity, Dust and Smoke Concentration, DPM, Humidity, etc.	Gas Sensors, Temperature Sensors, Humidity Sensors, Airflow Sensors, Pressure Sensors, Smoke Detectors, Dust Detectors, etc.
Fire Detection	Gas Concentration, Smoke Concentration, Temperature, etc.	Gas Sensors, Smoke Sensors, Temperature Sensors, etc.
Personal Equipment	Body Temperature, Heart Rate, Respiration, etc.	Temperature Sensors

Table 5. Examples of IoT applications for heat monitoring

Reference	Year	Sensor Deployment
[45]	2009	Sensor embedded in the helmet.
[46]	2013	Static and mobile robot sensing nodes.
[47]	2017	Fixed sensor nodes.
[48]	2018	Sensors embedded in the helmet.
[49]	2018	Sensors embedded in the helmet.
[50]	2019	N/A
[51]	2020	Portable sensors
[37]	2021	Sensors embedded in the helmet.
[12]	2023	Monitoring robot

based on machine learning, which includes real-time monitoring components such as fan frequency regulation and associated branch air resistance regulation.

Data collection in mine ventilation systems involves various methods and technologies. For instance, machine vision is utilised to process measurement data of the geometry of mine airways and mining equipment using various sensors, including visual, inertial and LiDAR sensors and their combinations.

The elevated temperatures and humidity levels prevalent in underground environments can pose a significant threat to the health and safety of miners. To address this issue, the mining industry has explored the use of IoT technologies to monitor and manage the thermal environment in underground mines. The implementation of IoT-based temperature and humidity sensors can provide real-time data on the thermal conditions within the mine Table 5.

Mine ventilation, employing AI technologies, plays an essential part in predicting harmful situations like fires. However, identifying emission locations and quantities can be challenging due to the geological, geographical, and operational factors of underground mines[52].

Air quality prediction in mine ventilation systems is addressed using various AI and machine learning techniques. For instance[53], an IoT system has been proposed

for underground mine air quality pollutant prediction based on Azure machine learning. Additionally, an IoT system integrating pollutant assessment and forecasting features using an Artificial Neural Network (ANN) model was also proposed for air quality monitoring. These systems aim to enhance the prediction and management of air quality in mines.

Machine Learning (ML) techniques identify patterns in data related to gas concentrations, airflow rates and other environmental parameters to detect anomalies and potential hazards. Pattern recognition in mine ventilation systems is addressed using various AI techniques. For instance, AI offers the capability to discern hidden patterns, adapt to changing conditions and provide forecasts amidst uncertainty. This capability is increasingly applied to mine ventilation tasks, as evidenced by a bibliometric analysis of publications in the past decade[54]. Additionally, machine vision is utilised to process measurement data of the geometry of mine airways and mining equipment using various sensors, which can be further used to estimate changes in mine air resistance[55]. The paper discusses studies on coal fires, methane explosions in coal mines and the prediction and prevention of spontaneous combustion in coal mines. Various techniques such as support vector machines, neural networks and Support Vector Regression (SVR) models were used to analyse temperature distribution, gas concentrations and heating rates in coal mine gobs to predict the risk of spontaneous combustion. The SVR model, particularly when optimised with Particle Swarm Optimisation (PSO), showed high prediction accuracy and generalisation ability in comparison to other models like Backpropagation in Neural Networks (BPNN) and Multiple Linear Regression (MLR)[56]. A thorough field investigation is conducted in this study to gather environmental data from three underground coal mines. Using the mining survey data as input, Genetic Programming (GP) is used to establish a relationship between environmental factors and heat stress. The results show that there is a strong correlation between the measured and anticipated heat stress in GP, suggesting that GP is a useful tool for predicting heat stress in underground mines[57]. The proposed method combines supercomputing and ML to predict fire smoke spread in mine tunnels. Four ML models were trained and applied, with Randon Forest (RF) and Support Vector Machine (SVM) models showing the best performance in predicting backflow and back-layering length. The Artificial Neural Networks (ANN) model showed the best performance in predicting back-layering length. The method reveals that ventilation velocity and tunnel inclination angle are critical factors affecting fire dynamics[58]. The study utilises a hybrid numerical method and Adaptive Neural Fuzzy Interface System (ANFIS) for accurate prediction of Wet Bulb Globe Temperature (WBGT) in underground mines, demonstrating its effectiveness in predicting mine air thermal conditions.

Fuzzy logic is applied in several ways within mine ventilation systems:

1. Fire Hazard Prediction[59]: Introduced a novel fuzzy logic system for underground coal mine fire hazard prediction, which was integrated into a wireless monitoring setup. The input parameters for this system included air temperatures and impurity concentrations.
2. Methane Accumulation Hazards[60]: Developed a system based on fuzzy logic and the ANFIS to forecast methane accumulation hazards over a longwall.
3. Ventilation Plan Optimisation[61]: Utilised fuzzy logic to optimise and evaluate the mine ventilation plan under conditions of a large number of varying parameters.
4. Reliability Allocation[62,63]: Employed fuzzy mathematics and a Monte Carlo simulation approach to develop a model for scientifically allocating reliability practices in mine ventilation system design.

These applications demonstrate the versatility and effectiveness of fuzzy logic in addressing various challenges in mine ventilation systems.

4.1 Reinforcement learning

Reinforcement learning is applied in mine ventilation systems to dynamically adjust mine airway resistances. For example[64], Deep Reinforcement Learning (DRL) is applied to adjust mine airway resistances dynamically, showing smaller errors compared to other algorithms. This was demonstrated in a ventilation network with 153 branches.

One widely recognized use of AI in mine ventilation is the improvement of ambient air quality control through the application of sophisticated data analysis techniques. To find intricate patterns and links that were previously challenging to detect using normal statistical approaches, sophisticated AI algorithms can process enormous amounts of data collected from numerous sources, such as air monitoring stations and sensors. Mine ventilation engineers may obtain deeper insights into the factors influencing air quality and use these AI-powered analytical capabilities to help them make more educated decisions and put more effective management plans into place.

Additionally, the effectiveness and dependability of mine ventilation operations can be greatly increased by integrating AI-based learning systems. To anticipate possible fan failures or performance degradation, AI-powered predictive maintenance models can evaluate sensor data and operating conditions. This enables proactive maintenance and lowers the likelihood of unscheduled downtime.

AI algorithms are also capable of simulating and modelling the intricate airflow patterns seen in mines. These algorithms take into consideration a wide range of variables, including the mine's properties, the ventilation system configurations and the constantly shifting environmental conditions. Mine ventilation engineers may fine-tune their systems to achieve ideal airflow, optimising efficiency and safety while decreasing energy usage, by leveraging these AI-powered simulation and optimisation capabilities.

AI-driven solutions are not only improving operations but also significantly increasing mine ventilation system safety. Monitoring and anomaly detection systems driven by AI can continuously examine operational parameters and sensor data to spot possible risks or variations from standard operating procedures. These systems use sophisticated pattern recognition algorithms to identify minute changes or patterns that can point to future problems. This allows mine ventilation engineers to take preventative action and lower hazards before they become more serious.

Furthermore, mine ventilation engineers can make quicker and better-informed decisions in emergency scenarios by integrating AI-based decision support tools. These technologies serve to reduce the impact of catastrophes and guarantee the safety of mine workers by processing massive volumes of real-time data quickly, analysing potential scenarios, and making recommendations for the best course of action.

5.0 AI Limitations

Author in[52] also discusses the limitations of current AI applications in mine ventilation, primarily focusing on small ventilation networks. It highlights the need for future research to explore the effectiveness of AI technologies for large-scale mine ventilation networks with thousands of branches.

5.1 Hardware Issues

IoT is an innovative technology that has several technical problems in real-world implementations. Sensors and communication devices should be robust and intrinsically safe because certain underground mines include explosive gasses, dust and humidity (particularly for coal mines). One of the main obstacles to IoT applications in deep mines is the limited power supply. Currently, power cables provide the majority of the electricity used in underground mining operations because most renewable energy sources such as sun, strong wind, and hydropower are not available underground. As a result, electronic equipment associated with the IoT that is located in underground mines must be powered by cables or have batteries, even though power-saving, miniature, low-power wireless sensors and communication modules have been created for the IoT.

5.2 Network Connection

For IoT systems that operate underground, an effective and efficient network connection is essential. Wireless signal propagation is weak in constrained tunnels and can be impacted by metal, despite the availability of multiple communication methods. While the low data rate can cause data congestion and time delays, the limited network coverage significantly raises the complexity and cost of network development. Hence, more study on cutting-edge RF communication technologies like 5G and LoRa is required to enable affordable and instantaneous subterranean communication.

5.3 Data Management

The challenges associated with integrating data from diverse sources in underground mines include the existence of data silos and the massive amount of data. Data silos refer to incompatible data distributed across different platforms, which can be a result of legacy systems operating for extended periods. This leads to inconvenience in data gathering and data management. Additionally, the prevalence of IoT applications can lead to an unprecedented increase in data categories and volumes from various information systems, exacerbating data silos and significantly increasing the workload of data processing[65].

6.0 Conclusion

The successful application of AI for worker safety in underground mines is a fundamental requirement for the major advances in mining operations that are expected within the next decade. The ongoing challenges that continue to be faced by mines, such as those related to ever-deepening mines and more complex ore bodies, require advanced solutions, and AI is providing these. However, a key shortcoming in this respect is how AI can be effectively integrated within operational mines. Such integrations are not trivial and require specialised data, software and/or hardware that match levels of data quality, model performance and novel model outputs to industry standards in a cost-effective manner.

This paper presents the recent applications of AI for worker safety in underground mines, with the facts and performance of several major case studies that leverage advanced AI models to improve safety at operational mines. The specific problems that are addressed include mine ventilation, gas management and worker health management.

A significant trend in the exciting field of AI for worker safety in underground mines is the increasing emphasis on automating the actions recommended. In this regard, one of the challenges concerns the integration of AI models for worker safety in complex, recursive manners that ensure multifaceted decisions account for and address the requirements of other common Health and Safety (H and S) concerns (such as production performance and environmental issues) consistently and constructively.

7.0 References

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