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REVIEW

Ventilation Monitoring and Control in Mines

Mahesh Shriwas[1] · Christopher Pritchard[2]

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Abstract

Ventilation monitoring and control in mines are becoming an integral part of day-to-day activity for maintaining health and safety of miners. The authors evaluate potential real-time monitoring solutions for detecting and reducing diesel particulate matter, mine fires, and dust in situ, and examined the state-of-the-art use of ventilation monitoring and control in underground mines for detecting and reducing air contaminants to acceptable regulatory limit. Authors review relevant documents, including research papers, trade publications, and manufacturers' website-based information, to identify research gaps. The authors also evaluate contemporary sensors (airflow, gas, dust, silica), control system and software technologies, data transport systems, Industrial Internet of Things, ventilation network simulators, and control devices to identify potential health and safety research gaps. In this study, examples of some mines from Canada, Australia, and the USA are included where ventilation monitoring and controls have been applied. Overall, this review identifies multiple challenges and research gaps in applying mine monitoring and control systems that could be the focus of future research, offering potential improvements to miner safety and health and financial benefits.

Keywords Ventilation · Monitoring · Control · Sensor

1 Introduction

Underground metal/nonmetal (M/NM) mines continue to expand production by employing larger equipment in greater numbers and mining deeper or more extensive mineral deposits, challenging existing ventilation systems to maintain workplace air quality. Overexposure to diesel particulate matter (DPM), respirable silica quartz, dust, carbon monoxide (CO), and nitrous oxides (NOx) continues to occur [1, 2].

Recent Mine Safety and Health Administration (MSHA) compliance sampling indicates that US M/NM underground mines continue to exceed DPM and silica exposure limits for certain occupations. Between 2010 and 2015, 288 DPM and 242 respirable silica quartz citations were issued with associated fines of over a half a million dollars [3]. Negative health effects from overexposures and the noted cost of MSHA citations, in addition to hazards such as heat, humidity, and reduced visibility, highlight the need for a more sophisticated approach to real-time ventilation monitoring and control. State-of-the-art ventilation solutions depend upon an informed selection and integration of ventilation-related sensors (airflow, gas, and DPM), data transport systems, control devices (fans, regulators, filtration, and cooling units), and control systems (software and hardware). Mines face challenges in evaluating system components and their integration with existing infrastructure, reliability of sensor data, and conducting cost-benefit analyses of the various technologies.

The authors reviewed relevant papers and manufacturers' websites to evaluate currently available monitoring and control components and applications used in Canadian, Australian, and US mines. The objective was to define the current state of monitoring and control system technology and use, identify existing health and safety application gaps for future research, and analyze improved ventilation solutions that could result in a safer and healthier mine environment.

Currently, there are no common mechanisms to control or mitigate short-term high exposures to contaminants. Repeated short-term exposure to these high levels of airborne contaminants over long periods can lead to serious health issues, which are documented in several studies [2, 4, 5]. Mines often attempt to minimize exposures by sending more fresh air to the general working areas where high contaminant concentrations are detected. Mines often attempt to minimize exposures by sending more fresh air to the general working areas where high contaminant concentrations are detected.

✉ Mahesh Shriwas
mshriwas@alaska.edu

[1] University of Alaska Fairbanks, Fairbanks, AK 99775, USA

[2] Dayton, USA

Toxic fumes are produced from blasting operations in underground mines which poses one of serious concerns for the safety of miners. Considering the large tonnage of rocks and toxic fume produced from blasting operation, it is important to dilute the contaminants to threshold limit value (TLV) by analyzing and designing primary and auxiliary ventilation systems. The ventilation requirement for rock blasting operation in mines depends upon the accurate determination of noxious gases produced and threshold limit value (TLV) of gases [6]. The most common gases are carbon dioxide, carbon monoxide, oxides of nitrogen, hydrogen sulfide, sulfur dioxide, hydrogen, methane, and nitrogen. Concentration of noxious gas other than carbon dioxide is not allowed to exceed the threshold limit value as specified and applied by the American Conference of Governmental Industrial Hygienists in "Threshold Value for Substance in Workroom Air" [7]. Equation 1 is used to calculate the ventilation requirement for diluting the contaminant whose ratio of initial concentration to TLV will be the highest. The other contaminants are diluted to their respective TLV with the same calculated ventilation requirement.

$$Q=\frac{Q_g(1-TLV)}{\left(TLV-B_g\right)} \tag{1}$$

where

Q: ventilation quantity requirement of fresh air, m^3/s
Q_g: contaminant flow rate, m^3/s
TLV: threshold limit value of the contaminant, %
B_g: concentration of the contaminant in the normal intake air, %

Real-time monitoring and control allow mines to monitor contaminants and implement changes in local or mine-wide ventilation in real time.

2 Monitoring and Control System Evaluation Areas

In this study, the following ventilation monitoring and control system categories were examined:

- Sensors: air velocity (airflow), gas, DPM, dust, and silica (quartz)
- Large-scale ventilation control systems
- Wireless data transport systems
- Industrial Internet of Things (IIoT)
- Ventilation network simulators
- Ventilation control devices

2.1 Sensors

Air Velocity Sensors Airflow measurement is used to ensure ventilation M/NM standard compliance for controlling contaminants [8]. Most mines do not use airflow sensors to determine velocity, but rather use handheld vane anemometers or smoke tubes. These methods offer flexibility, have been the industry standard for years, and are performed infrequently, but they are also time and labor intensive. Occasionally, mines use airflow sensors at key locations such as main fans and regulators, which MSHA accepts in lieu of a physical measurement.

Commonly used airflow sensors for mining applications measure velocity based on either a single-point (single value) or two-point measurement (average value across the entry) and also to detect airflow reversal while requiring only moderate maintenance and calibration. Any single-point measurement must be calibrated to a measured average velocity across the airway [9]. For real-time monitoring and control, airflow sensors need to be integrated with data analysis software and the ventilation and control system.

Gas Sensors Measurement of critical mine gasses is an MSHA regulatory requirement, with the most commonly used method of determining concentrations being routine spot readings with portable handheld devices. However, MSHA may accept sensors connected to a monitoring system in lieu of a physical examination of the specific work area.

Many types of gas sensors are available for underground mine application [10–14]. Each has certain capabilities and limitations. For example, electrochemical sensor—narrow or limited temperature range, short or limited shelf life, cross-sensitivity of other gases, slow start-up if depolarized; infrared sensor—expensive, increases maintenance cost in high humidity and dust area, affect the performance when water vapor condensation occurs on sensor; catalytic sensor—requires presence of oxygen, degrades in prolonged exposure to high concentration of combustible gas. Thus, the suitability of a given sensor depends largely on the individual gas being measured. Failed sensors and sensors out of calibration send inaccurate information to the monitoring and control system, inducing poor control system response or management actions.

Regarding mine fire detection, discrimination from normal diesel equipment operation is difficult, as CO is the common post-combustion gas measured. Adding smoke detectors and improving monitoring software analysis are an option to identify mine fires from sources other than diesel engine emissions.

DPM Sensors DPM is often the critical contaminant to monitor in relation to maintaining air quality; therefore, its real-time monitoring integration into a monitoring system is necessary to effectively initiate engineering control measures. Currently, there are three real-time DPM sensors commercially available: (1) the Pinssar READER [15], a laser-light scattering photometry instrument, (2) the Sunset Laboratory Inc., Model 4 Organic Carbon and Elemental Carbon (OCEC) Field Analyzer, and (3) the Magee Aethalometer [15–17]. The Magee has multiple detection capabilities that can differentiate combustion types such as timber fires from those of diesel emissions, which make it particularly valuable in a mine environment.

For effective control of DPM in a mine workplace, an affordable and reliable real-time mine duty instrument is needed. The Sunset Laboratory OCEC has been shown to be effective in laboratory and field work [18]. Presently, the Pinssar and Magee instruments cost in excess of $30,000 each, making them too expensive to be widely utilized. Currently, short-term DPM exposures of less than one shift are determined by using either the FLIR/Airtec [17], which gives a real-time readout during the sample period (usually a shift or less), or by collecting conventional NIOSH 5040 filter samples for the full working shift, which must be analyzed in a laboratory [19]. The FLIR/Airtec is not practical to be utilized in a monitoring and control system due to being a battery-powered unit and overloading of the cassette, but the technology is promising due to its real-time results.

Dust Sensor Occupational dust exposure measurement is a regulatory requirement to ensure MSHA compliance for nuisance or harmful dusts. For this analysis, two types of personal dust monitors were evaluated: (1) the ThermoFisher pDR-1500 and (2) the PDM3700 [20, 21]. Although both are portable laboratory instruments for short-term sampling, their technology shows promise for mine monitoring and control applications. For information purposes, we also note that Maestro has the DustMon [22], which monitors mine dust levels to control dust suppression systems. However, the instrument's capability is not defined as far as total or respirable ranges, and although it may have potential if calibrated for respirable dust, that possibility was not evaluated. Instruments such as the ThermoFisher pDR-1500 and PDM3700 noted above are available for short-term real-time personal or area sampling.

Silica (Quartz) Overexposure to silica can lead to silicosis, a potentially fatal lung disease. Presently, real-time silica dust measurement is under development and not available for mine monitoring installations. Mines continue to utilize shift-based samples, which require laboratory analysis to determine compliance, delaying access to exposure information needed to make timely ventilation adjustments to avoid overexposures. Therefore, continued research and development is needed before silica monitoring can be included in mine monitoring and control systems.

2.2 Large-scale Ventilation Control Systems

Software capable of analyzing ventilation data (monitoring) and adjusting ventilation accordingly (control) is commercially available [23–29]. Adjustment of ventilation in response to vehicle and miner status and location information is generally referred to as "ventilation on demand" (VOD) [30]. Utilizing input from pre-programmed scenarios, ventilation monitors, data transport, and software analysis, VOD is designed to meet equipment airflow requirements or predetermined production plans. Software algorithms determine airflow requirements based on vehicle tracking and personnel data acquired from the monitoring or tracking system, which adjusts ventilation airflow controls to meet defined airflow requirements. The impetus for Canadian VOD development was to lower costs related to mine ventilation, to reduce the national carbon footprint, and to improve utilization of mine airflow. The VOD concept has been used in various situations throughout the world for airflow monitoring and control applications and is often referred to in the USA as airflow optimization [31]. However, as mentioned previously regarding the Magee Aethalometer, complications due to a mine fire pose challenges to this method.

2.3 Wireless Data Transport System (Wireless Data Communication Systems)

In addition to traditional hardwired methods, mines are leveraging wireless communication systems for data transport (backhaul) needed for monitoring and control. Wireless communication systems can be categorized as two basic types: leaky feeder and node based [32]. An overview of each type as applied to data backhaul is provided below.

Narrowband data radios can leverage leaky feeder systems for backhaul and are available in both serial and Ethernet configurations, allowing for data rates from ~ 4 to 256 Kbps depending upon configuration, modulation type, and regulatory restrictions. The advantage of data radios used in conjunction with leaky feeder systems is that no special equipment or modifications to the leaky feeder system are needed. Data rates in excess of 20 Mbps are possible using Ethernet over leaky feeder (ELF) technology, but highly specialized equipment is required, and splices into the leaky feeder coaxial cable are necessary wherever an Ethernet connection is desired.

Node-based communications systems employ broadband data radios as connections, or redistribution points, to a communication network backbone. Data backhaul rates vary greatly, from 250 Kbps to > 200 Mbps, depending on the networking protocols used as well as how the nodes interface with the main communication network.

Besides the advantage of high data rates for node-based systems, there are many commercially available end devices that support Internet Protocol (IP). Also, flexibility of node deployment is a consideration. When hardwired infrastructure is available, nodes can easily be installed. If hardwired infrastructure is not available and the highest possible data rates are not critical, some node-based systems allow for network extensibility through multiple node data hopping.

Many underground wireless communication systems and wireless sensor manufacturers use proprietary signaling schemes (protocols). This diversity in protocols combined with the lack of standards for underground wireless systems presents the potential for problems involving interoperability and compatibility, commonly referred to as electromagnetic interference (EMI) or electromagnetic compatibility (EMC). EMI or EMC problems could also arise between wireless systems and sensors and existing mine infrastructures.

2.4 Industrial Internet of Things

Mines have also begun to leverage the Industrial Internet of Things (IIoT), also known as the Industrial Internet [33] for wireless mining automation and control. While rather broad and ambiguous, the term IIoT is a concept generally used to describe a network of smart physical objects or "things" that can exchange data—typically wirelessly—between each other, control systems, and/or operators [34, 35]. IIoT is currently being used in the mining industry for autonomous vehicles, tracking personnel and assets, providing remote monitoring and diagnostics for haulage equipment, and VOD [35].

2.5 Ventilation Network Simulators

Ventilation network simulators are becoming an integral part of ventilation monitoring and control systems. Some simulators can receive sensor data and update the network with various attributes such as airflow and contaminants, but have limited capabilities in connecting to monitoring and control systems at the present time. Those attributes help in determining the ventilation status of the mine for maintaining the health and safety of miners in timely manner. The capabilities of those simulators can be enhanced by incorporating customized program in connecting to monitoring and control system.

2.6 Ventilation Control Devices

Fans are used to facilitate airflow control, and for effective application in monitoring and control systems; they should be equipped with either a variable frequency drive (VFD) or an in-flight blade pitch adjustment (BPA).

Regulators/Louvers are physically adjusted to control the airflow distribution by changing mine resistance. Louver openings and the resultant airflow are governed by control software analysis of the contaminant level and equipment demand.

Scrubbers are used to remove harmful materials such as dust and DPM from mine airflow to improve air quality. In-mine testing of a supplied dry scrubber found an average DPM removal of 80–96% [36], showing promise for integration into a monitoring and control system should a real-time DPM and/or dust monitor be available. Water-based scrubbing systems can remove dust, but at a much lower efficiency [37]. High-efficiency particulate air (HEPA) filters are also an option. Importantly, scrubbers require regular maintenance and filter changes, which increase costs.

Heaters/coolers can control temperature and make the workplace more comfortable and safer through the data acquired from temperature sensors or personnel/equipment tagging via radio frequency identification (RFID).

The above-noted ventilation equipment and control technologies are in common use and readily available for monitoring and control system application, as described in Section 2.2.

3 Examples of Large-scale Monitoring and Control Application in Mines

3.1 Canada

Vale Inc. Coleman Mine conducted a VOD pilot project to reduce ventilation costs, to increase flexibility of the ventilation system, and to allow mine expansion without increased infrastructure. The mine monitored air velocity (airflow), dry and wet bulb temperature, relative humidity, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NO), and control of VFD fans and louvers [38]. Allen and Tran estimate that this project could potentially result in an annual savings of $300,000.

Xstrata Nickel Rim Mine also implemented a VOD system for airflow monitoring and control. The system consists of ultrasonic airflow sensors; CO, O_2, and NO_2 gas sensors; primary and auxiliary fans equipped with VFD; regulators; control systems; and RFID tracking devices. The 2011 trial has shown savings of 10,140 MWh annually [39].

Goldcorp's Éléonore Mine decided to build a "connected mine" utilizing radio frequency (RF) tags on miners and mobile equipment to monitor and optimize airflow underground and support the VOD system. Improved air usage dropped airflow from 1.2 million cfm to 600k cfm, eventually saving 1.5 to 2.5 million dollars per year [40]. Through the use of the Industrial Internet of Things (IIoT), the mine is able to obtain information on equipment operating data for running diagnostics and keep better track of employee locations, reducing emergency response time and effort.

3.2 Australia

Gwalia Gold Mine implemented a VOD system to adjust airflow to meet production needs on a shift-by-shift basis. Air velocity and gas sensors, primary and secondary fans with VFD, roller type regulators, and a Ventsim network simulator were integrated through the leaky feeder system and software. Real-time sensor data is accessed by the Ventsim simulator, which continually updates simulation output. Software implements automatic control of fan speed and regulators to meet system airflow needs. Annual mine ventilation costs reductions of $7.2M and $0.23M were achieved for primary and secondary fans, respectively [42]. Identified disadvantages were that when fan speeds and regulators were changed, there was a significant time delay at this mine of up to 10 min before mine airflows reached a state of equilibrium [41].

3.3 USA

Waste Isolation Pilot Plant (*WIPP*) is designed to provide safe underground disposal storage for transuranic nuclear waste generated by the US Defense Department [42–47]. WIPP also used a mine weather station to measure natural ventilation pressure (NVP). Differential pressure sensors were utilized to measure the pressure drop between airflow splits to prevent critical radiation contamination between mine operating areas. Airflow distribution and differential pressure between air splits were controlled either manually or through dampers operated by electric actuators. WIPP used dry dust filtration units with surface-installed HEPA filters for filtering mining face dust to minimize transport out of the mine. HEPA filtration is required to limit any potential radiation release into the atmosphere.

Barrick Goldstrike Mine's extensive mine-wide monitoring system's primary objective is to supply a large quantity of air to ventilate workings where heat, CO, and SO_2 are liberated [48, 49]. Barrick installed ultrasonic airflow sensors on several mining levels, ramps, and main intersections, and where airflow tends to reverse, sensors were bi-directionally configured. The mine installed gas monitors to measure CO_2, SO_2, O_2, and CO. Several remotely adjustable regulators were installed at main vent raises, and actuators were connected to a digital communication network. RFID tags from mobile equipment and miners are detected by a sensing system, and tracking software processes and passes this information on to a display system, which allows the mine to locate and view mobile equipment in real time. Later in the process of using this mine-wide monitoring system, improved control of equipment such as fans, compressors, and refrigeration was added.

Edgar Experimental Mine, in collaboration with NTT Innovation Institute, Inc. (NTTi^3) and the Colorado School of Mines, conducted a 6-month field investigation to implement an IIoT solution for its VOD system. The prototype solution, which added intelligence to the existing network and sensors as well as enabling variable speed control of fans, showed a 10% energy savings in just 2 weeks of the pilot program, along with a projection of 120 man-hours saved per year. It was also projected that mid-sized mines, not currently attempting to optimize airflow, could save 30% in energy costs [50].

Although not commonly utilized worldwide in underground mines, ventilation monitoring and control has had success in many operations through the application of multiple technologies with good results, and is being considered for expanded use in current operations and incorporation in new mines. Most importantly, the application of a ventilation monitoring and control system on a small scale in the working face—where gas, dust, and fume concentrations are usually highest—has a high potential to greatly improve miner health and safety in a timely manner and at an efficient cost.

4 Identified Technology and Research Gaps

Based on this evaluation of smart monitoring and control systems, both in installations and as described in the literature, the following technology and research gaps were identified.

(1) Real-time DPM and silica quartz dust monitoring devices have not been integrated into mine monitoring and control systems due to the unavailability or excessive cost of mine duty instruments. Currently, real-time DPM monitoring instruments such as the Magee Aethalometer, the Sunset Laboratory OCEC, and the Pinssar are available for mine installations. Dust monitors such as the ThermoFisher pDR-1500 and the PDM 3700 can be used for short-term real-time applications, but mine operators express an urgent need for development of real-time, mine duty, economical DPM, and silica dust monitoring equipment.

(2) To effectively distinguish a mine fire from the heat and emissions of normal operating diesel equipment, additional CO emission discriminating technology or smoke detectors must be incorporated.

(3) Prediction of atmospheric conditions between sensors is difficult with the limited number of installed sensors and can be complicated by data gaps from faulty or inoperable instruments. Mathematical modelling of sensor data is needed to extrapolate contaminant levels throughout the mine from information gathered from reliable gas and airflow sensors, and integration with refined network simulation models.

(4) Investigation is needed for potential issues involving interoperability and compatibility of EMI or EMC between the mine wireless systems and mine infrastructure systems.

(5) Wireless sensor networks face challenges that include handling of large data, creation of a high spatial resolution, installation costs, and poor data security.

(6) Long-term storage and advanced analysis of monitoring data is needed that can identify trends over and above simple low- and high-alarm settings, and then identify potential emergency situations such as mine fires, explosions, or dangerous exposure levels on a local or mine-wide level in time to mitigate those circumstances.

(7) Surface fans are not as fast or effective as underground booster and auxiliary fans in responding to diluting monitored parameters due to time delays between fan and regulator adjustments and subsequent ventilation improvement at the workplace. The time required for the ventilation system to equilibrate changes needs to be studied and taken into account to effectively understand the effects of airflow changes on the individual workplace.
(8) Integration of monitoring and control systems with ventilation network models for mine emergency planning is needed. Mine emergencies, especially mine fires, require accurate information for management to make effective decisions to adjust ventilation and direct mine rescue efforts. Allowing modelling of ventilation system changes to observe changes in contaminants during an emergency will improve miner safety and improve emergency response.
(9) Better knowledge of the potential for problems involving EMI or EMC between the diverse types of mine monitoring and control and wireless systems is needed.

5 Conclusions

This review evaluated a wide variety of airflow sensors, gas sensors, control systems, data transport systems, and ventilation simulators for ventilation monitoring and control applications. As detailed in this review, multiple sensors are available for most ventilation-related monitoring needs, allowing operators to determine the status of mine atmosphere contamination as inputs and use this information to effectively adjust ventilation control hardware. Methods to integrate sensors, data, software, and hardware are well developed and readily available. However, proprietary software may not allow for re-configuration to suit customer needs, and in practice, minimal analysis of mine monitoring data is undertaken, limiting the benefit of this large volume of information that is also expensively acquired.

Leaky feeder, fiber optics, and wireless systems are effectively used for data transport and to operate control systems. Mines in Canada, Australia, the USA, and other countries have implemented ventilation monitoring and control with good results and further progress is planned.

Continuous monitoring equipment for DPM, silica, and dust monitoring needs to be developed and refined for effective application of local workplace monitoring and control and large-area monitoring and control (VOD). In addition, further integration of network modelling tools and discrimination between vehicle emissions and fire contaminants is essential to safely apply monitoring and control systems.

This review concluded that hardware and software do not provide a complete answer, as effective human oversight and an interface to the ventilation system is critical for safe operation in day-to-day operations and during mine emergencies.

The authors encourage future research on identified research gaps to make monitoring and control systems effective for evaluation of numerous mitigation scenarios. With applications and improvements as described above, this review suggests that application of effective monitoring and control systems will lead to enhanced miner safety and health.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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