International Journal of Mining Science and Technology 25 (2015) 165–169

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Invited Paper

The practice of mine ventilation engineering

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ARTICLE INFO

Article history:
Received 2 June 2014
Received in revised form 19 August 2014
Accepted 17 October 2014
Available online 14 March 2015

Keywords:
Modern ventilation
Ventilation on demand
Diesel
Airflow evaluation
Monitoring system

ABSTRACT

The practice of ventilation is continually evolving with new technological advances developed in the mining industry. In recent years the advances in diesel engine technologies, ventilation modeling software, and ventilation management capacities have redefined the historical methods used to evaluate systems. The advances re-evaluate previous methods used to calculate the airflow requirements for the dilution of diesel exhaust fumes. Modeling software has become an integral part of planning and developing ventilation systems in partnership with graphical mine design software packages to generate realistic representations of the mine. Significant advances in ventilation control strategies through remote sensors and monitoring capabilities have been developed to results in cost savings. Though there has been much advancement in mine ventilation technology, the practices and basic ventilation principals enacted through the ventilation engineer cannot be placated with technological advances only.

1. Introduction

Dr. Malcolm McPherson described the objective of any underground ventilation system as a system that will provide airflows in sufficient quantity and quality to dilute contaminants to safe concentrations in all parts of a mine where personnel are required to work or travel [1]. In concept this seems easy enough. However, as mines become deeper, hotter, gassier and more mechanized, this concept can become quite challenging. Ventilation engineers need to have a good understanding of mine ventilation practices that include dust control, heat stress management, refrigeration and/or air heating, control of mine gases, radiation control, explosive gas and dust and mine fire risks, escape and rescue planning, noise minimization, fan operation and theory, and mine ventilation economics. The engineer must have an understanding on main and auxiliary fan practices. In addition, the engineer should have an understanding of occupational exposure limits for airborne pollutants and an idea of sampling for these pollutants.

Ventilation of any underground mine is a process of identifying the potential hazards from a mining system and implementing a ventilation system that ensures the health and safety of the mine worker. To this end, a number of new advances have been made to benefit the engineer in achieving this goal. To understand the issues with providing a healthy environment, one must first evaluate the hazards.

In mines, we rarely have a choice in deciding the properties of the ore or coal body, the surface climate, the inflow of strata water and/or gas, and the physical and chemical properties of the rock. What we do have control over are the design factors, such as, method of mining, layout of airways, rate of rock fragmentation, and types of vehicles to be used. However, it is often the case that much of the design will be driven by production considerations and not by ventilation concerns. Ventilation is often thought of as an expense and not a means to a profitable mine. This thought, however, is not justified since it is obvious that a healthy workplace results in greater productivity. This is challenging to prove in practice since it is difficult to quantify the difference in productivity between a poor and good ventilated mine.

In today's modern mines, the engineer needs to have solid understanding of legislative requirements and "best" engineering practice. Common parameters legislated can include gas and dust concentrations, thermal conditions, Diesel particulate matter (DPM), and minimum airflow rates. The engineer needs to understand these requirements when designing a ventilation system. Good practice means incorporating a ventilation system that fulfills the legislative requirements even if there is no mine inspectorate to ensure the system is in compliance. Being complacent in the practice of mine ventilation can have severe, and possibly deadly, consequences.

2. Current trends in mine ventilation

In metal mines there is a trend for larger diesel equipment, increased production pressures resulting in a larger number of

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http://dx.doi.org/10.1016/j.ijmst.2015.02.001
2095-2686/

operating faces, the use of series ventilation to minimize airflow, increased regulations to lower respirable particulate dust (silica and/or DPM) [2], increased refrigeration requirements as mines go deeper [3], use of haulage ramp air as an intake or exhaust from sublevels, and an increase in electrical power costs that can drive designs to a minimal ventilation system.

In coal mines the trends include, improved real time communication and tracking systems for effective escape and/or refuge planning, applying inert gas injection to sealed gob areas to reduce explosive atmospheres, improved rock dusting application to minimize explosive dust, increased legislative requirements to control silica and coal dust exposers, and use of underground booster fans to enhance ventilation to working areas.

Some of the current state of the art work in ventilation addresses the trends presented above. Advances include:

- Ventilation on demand (VOD).
- Mine ventilation monitoring systems.
- Software for ventilation planning.
- Software to predict the impact of an underground fire.
- Advances in diesel engine technology to minimize DPM.
- Remote monitoring of long wall gob particularly when inert gas is injected.
- Energy savings regarding ventilation and air cooling systems.
- Real time monitoring of the underground environment including devices to measure dust and DPM.

2.1. Ventilation on demand

The concept of ventilation on demand (VOD) is to apply airflow to only the working areas of the mine while minimizing airflow to remaining areas. This concept is typically applied to metal/non-metal mines and not coal mines. The system can be as simple as one that turns on ventilation to a zone regardless of the work activity or a relatively complicated one that controls the flow based on air quality sensors. The later system usually requires fan motors on variable speed drives (or variable frequency drives-VFD), air gas sensors (e.g. carbon monoxide, oxygen, nitrogen oxides, etc.), airflow sensors, regulator and fan control systems, and equipment and personnel tagging systems. The concept is to provide airflow as needed during the mining cycle. For example, an LHD entering a stope would require a specific airflow rate. This airflow rate would be predetermined for the LHD. A regulator or fan would be opened to provide this airflow. The tagging system would identify the location of the LHD to ensure the flow is constant during its operation in the area. Air quality sensors monitor the air condition during the mining cycle. When the LHD leaves the area, these sensors will maintain the airflow rate until such a time as the air quality is acceptable and the regulator or fan can be turned down or off. This logic would apply to any operating equipment in the mine and for personnel. In addition, the primary fans would also have VFD control.

The cost of installing such monitoring systems and the maintenance to keep the system operational is high. Therefore, mines considering such a system usually take a phased approach. This approach is typically:

Stage 1 A VOD system that is remotely controlled. It requires less design up front than an automated system, but requires more moment to moment manual adjustments for optimization. This includes the installation of automation and instrumentation to remotely operate ventilation infrastructure such as fans, regulators, doors, and personnel tracking systems.

Stage 2 This represents a VOD system that is controlled by a list of predesigned modes or set points of operation. These modes or set points would be triggered by certain events such as a shift change, or mining activities such as pre/post blasting. These modes could be manually triggered, but would better be initiated by an automated system responding to appropriate initiation signals.

Stage 3 This represents a fully dynamic control system where airflow is continually controlled and balanced based on knowledge of equipment location and mining activities. This would be the most highly optimized stage resulting in an optimized reduction in wasted air.

Some calculations have shown that a fully automated VOD system can have an electrical power savings of up to 50% over a conventional mine ventilation system. The use of VOD for coal mines is far more challenging since many governments legislate minimum airflow quantities at strategic locations. Varying the flow could have serious consequences if the sensors or control systems are not operating correctly.

Tools available include computer software for ventilation planning and implementation of monitoring systems in the mine to evaluate fans, airflows, temperature, gasses, and other parameters in real time.

2.2. Ventilation monitoring systems

In some countries monitoring of certain fan operating conditions and/or air quality is mandatory. Continuous fan static pressure measurements are required at U.S. coal mines. In addition, monitoring of explosive gases in sealed gob and in entries is required. Other parameters measured can include carbon monoxide, carbon dioxide, oxygen, and methane. For metal mines, the gases measured are similar to above but may include sulfide gases and nitrates of oxide. Additionally, on conveyors smoke sensors are often included in the monitoring program.

Other parameters monitored are airflows at strategic underground locations and through fan systems, door and regulator positions, and air temperatures. Other parameters can include DPM and dust continuous monitors. Subsystems can include water flow and temperature for heat exchangers (water sprays) and fan data such as on/off and operating position if the motor is equipped with a VFD.

These systems allow for real time evaluation of the underground environment and can be used in a VOD system to provide ventilation flow control to minimize fan power costs.

2.3. Software for ventilation planning

In the past 5 years significant improvements have been made in software for ventilation planning purposes. As PC computers have become more powerful, users have become accustomed to better graphical interfaces and more tools to support ventilation planning. Mine ventilation networks are now developed with on screen graphic construction and/or importing of mine networks from mine design software and/or computer aided design (CAD) packages. The software results exactly resemble the mine layout in all three dimensions as shown in Figs. 1 and 2.

Network simulation requires training and practice, as well as a thorough understanding of the inputs that are required. As software becomes easier to use, it becomes more challenging for the user to be cognizant of its output. The old adage "garbage in" equals "garbage out" needs to be well understood. It is very easy for the engineer to accept the software default values as meaningful and allow the software to make basic engineering decisions as to the model parameters. This can be a dangerous practice. There is no problem using default values provided the user has set these up based on either measured information or basic engineering

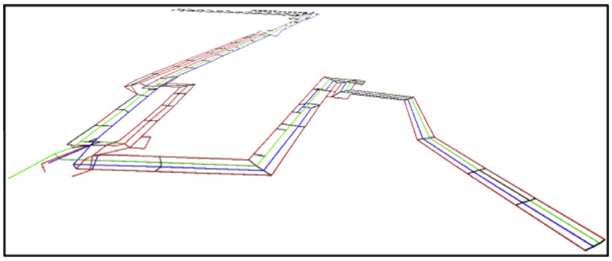

Fig. 1. Ventilation network model/diagram of small coal mine (VnetPC program).

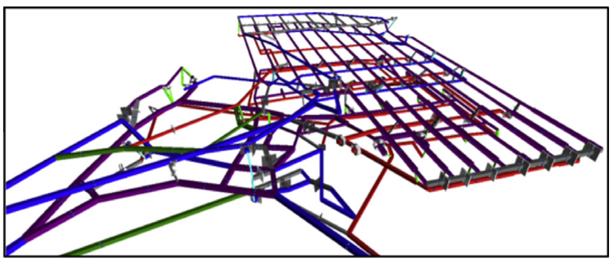

Fig. 2. Ventilation network model/diagram of large metal mine (VnetPC program).

principles. The user must be aware of the model inputs and the limits to the modeling if the model is to be accurate.

For existing mines, the network simulation needs to represent the actual mine system. To this end, the model needs to be verified against actual measured data. Validating a model is essential if the model is to be used for future projections. This validation can be achieved through a detailed ventilation survey or, as a minimum, through spot verification and friction factor calculations.

The purpose of network simulation is to predict the mine ventilation system at some future time. It is intended to provide mine management with the information needed to procure and install primary and booster fans, size raises and shafts, to determine the number of parallel airways needed for intake and/or return systems, and to evaluate the location of ventilation infrastructure, such as doors, regulators, and bulkheads or stoppings. In other words, the results of the modeling work will be used to determine the cost of implementing a ventilation system and the mining schedule to implement the system.

Simulation packages also have routines to support calculations related to mine gas distribution, radon decay products, and mine environmental conditions (e.g. wet and dry bulb temperature and worker heat predictions). Some can assist in sizing and locating heat exchangers and chilled water piping.

In addition to network simulations, more mining companies are using CFD simulation programs to solve complicated airflow problems in three dimensions. CFD analysis has been used to evaluate ventilation and contaminate concentrations around continuous miners, dust extractor systems, gas levels during an inrush of gas, assess shock losses of ventilation infrastructure (raises in metal mines and air crossing in coal mines), impact of in-gob gas movements based on bleeder road configurations, fan duct inlets and exhausts, hoisting skip effects on shaft airflows, air plenum designs, and fan inlet guide vanes. This is an example list of the powerful application of CFD studies in mine ventilation.

In the future it is expected that computer power will continue to grow resulting in additional software capabilities. Real time communication will increase along with Wi-Fi and Bluetooth technologies. This will result in real time airflow, air quality, personnel and equipment location, door and regulator settings, and other ventilation related information being available on virtually any device. PC-based tools are currently becoming mobile based tools with applications developed for tablet, smart phone, and smart watch applications. This information will integrate seamlessly with spatial data basis (cloud based) and will be available to mine planning and design teams. However, the experience and knowledge of the ventilation practitioner will always be required to issue commands and input data.

2.4. Mine fire simulation

In recent years there has been a significant increase in mine operators wanting to understand the effect of an underground fire on escape and refuge. This trend has resulted in fire modeling. A fire simulation package provides a dynamic representation of a mine fire and utilizes color graphics to show the distribution of combustion products, oxygen and temperature throughout the ventilation system. An example of a basic graphical fire simulation interface is shown in Fig. 3. Changes to the ventilation system, such as turning fans on or off, opening regulators, and other impacts can be added to the model. The models can simulate fire rich or oxygen rich fires and takes into account natural ventilation and buoyancy effects of fumes moving in inclined airways. This type of simulation is very technical and requires the engineer to have a good understanding of the products of combustion and other fire parameters. Because of the large number of assumptions in this type of modeling (e.g. what thermal heat is produced, how fast the fire burns and for how long, for example), the use of fire simulations packages should not be considered a precise science. Rather, it is a valuable way to evaluate the possible effects of a fire to ascertain the location of fire doors, location of refuge stations, planning escape routes and assist in evaluating the type of self-rescuer to be used.

Fire modeling is usually the result of a risk assessment at a particular mine. With a risk assessment, the probability of a fire can be determined along with the location of the fire. The fire simulation analysis will help understand the consequence of the fire. The modeling also helps evaluate fire mitigation alternatives and escape planning.

2.5. Diesel equipment and ventilation

Traditionally, ventilation requirements for modern, mechanized underground mines have been based upon the power of the diesel equipment fleet, with a multiplier (determined from empirical data collected and compiled over a long period of time or required by regulations) being applied in order to determine the total airflow volume requirements of entire mines and/or individual sections or working areas. Often, in the absence of unusual geographic,

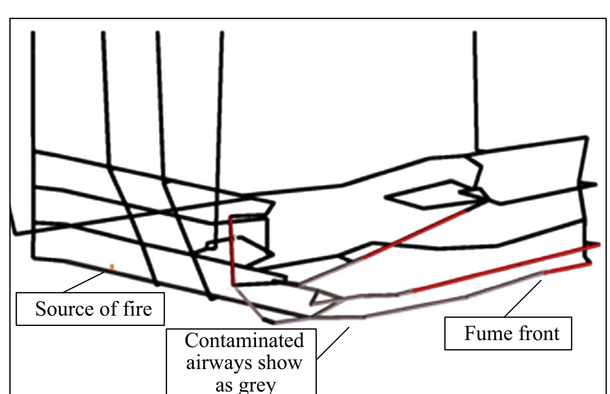

Fig. 3. Fire simulation graphical design view (mine fire program).

climatic or geologic conditions that warranted special consideration, the airflow required for the dilution of diesel exhaust products would provide sufficient ventilation for the entire mine. However, recent studies by the International Agency for Research on Cancer (IARC) and NIOSH regarding the relationship between exposure to diesel emissions and cancer in humans, coupled with additional scrutiny on "greenhouse" gas emissions, have resulted in changes to the regulations for engine and equipment manufacturers to provide cleaner burning and less polluting equipment (EPA Tier IV/EURO Stage IV). In some cases, this has resulted in the reduction of engine-out emissions by as much as 90%. While this reduction in particulate and gaseous emissions is significant, it is important to note that there is no equivalent drop in the ventilation rate (or requirement) of this magnitude.

All diesel equipment operating underground will also generate two other important contaminants; heat and dust, which are also mitigated primarily by the ventilation system. Whereas before the total quantity required for a given system could be determined based on the amount required for the dilution of exhaust gases from the diesel equipment, the calculation must now consider the heat generated by the equipment, and the removal of dust from the working environment in areas where other control measures (e.g., environmental cabins, filters, etc.) are not present. Although the total amount of airflow (quantity) may in some cases be reduced, the determination of the quantity required is now a slightly more complex and time-consuming process.

2.6. Power savings in ventilation

At many underground mines, operating the ventilation system continuously is a significant percentage of the power used. Up to 70% of the mine power can be devoted to primary fans, air chillers and other ventilation components. Power savings are achieved by reducing flow during times when no activities are occurring in that area of the mine and no contaminants are accumulating. The VOD section above describes this approach. Other areas where significant power savings can be achieved are with air cooling systems. Some refrigeration plants are currently being designed to manufacture ice during the evening and using this as water for the surface spray chambers. By producing ice during low electrical demand periods (and at a lower price) and melting and using it in the surface heat exchanger during high electrical demand periods has resulted in significant power savings at some South African mines.

Ventilation engineers need to be very cognizant in the design of ventilation and air conditioning systems to ensure efficient and cost effective systems are installed. The use of software to optimize ventilation and refrigeration systems is critical to optimizing these systems.

2.7. Current ventilation concepts for coal mining

The ventilation of coal mines and maintaining a safe atmosphere for the workers depends upon many factors outside of simply ventilating for equipment and blast fume clearances. Coal mine ventilation is primarily concerned with controlling explosive gas and dust, oxygen deficiency, spontaneous combustion and dust control (pneumoconiosis). Because explosive gas can be generated separately from the mining process, coal mines cannot and should not rely on VOD systems to automatically adjust fans and/or flow in the mine. Changing ventilation in a coal mine should be a manually controlled operation.

In many developed countries, government agencies mandate specific ventilation levels and conditions throughout a coal mine. In sealed areas of a coal mine or in areas behind a longwall the possibility of a buildup of explosive gas mixtures is of primary concern. Therefore, ensuring an inert atmosphere in gob areas is a primary concern. There are two thoughts to this process. Either the gob area is maintained at a very high explosive gas level (which is not explosive) or the area is kept well below the explosive gas level. The hazard with the first approach is that any gas leaking from the gob area to the active mine will transition through the explosive range. Such leakage often happens during periods when the surface barometric pressure is falling (creating a differential pressure between the sealed area and the mine airways). Because of this, more coal companies are ensuring the gob areas are kept well below the explosive gas levels by using bleeder ventilation systems. These systems intentionally apply intake air behind the mining areas to extract the gas and send it to the return. If these systems are not capable of maintaining the gas in a safe, low concentration then either draining the gas with drainage systems or injecting the area with an inert gas such as nitrogen may be necessary.

Methane drainage systems either use in-mine piping or surface drainage boreholes for transporting the gas away from the underground. The infrastructure includes pipes, monitors, controls and extractor pumps (if required). Software packages are available to assist with this design of such systems. The key elements to consider are where to locate the draining holes (across the coal seam or boreholes from surface or both) and understanding where the gas is coming from. It is very common that methane entering a coal mine is not entering through the seam being mined, rather from seams above or below the mined seam. The practice of hydrofracturing can also be enhanced the flow of gas to the drainage holes.

To ensure safe gob zones it is vital that a method be developed to continuously monitor the accumulation of gob gas. This is typically done with tube bundles that collect gas samples and transmit the data to a central monitoring system. Such a system is often used to control the nitrogen gas injection system.

Dust control in coal mines is critical to minimize the risk of long term lung disease to the workforce. To control dust, effective water sprays and operator isolation are important. Respirable dust, once airborne, is extremely difficult to control. Therefore, it is important that water suppression systems try to hit the mineral prior to generating dust, such as at continuous miner picks and conveyor transfer points. In addition, water sprays can be effective at generating "clean air" zones where the spray pushes water and air towards the dust source and away from the operator.

Another hazard within some coal mines is the risk of associated with spontaneous combustion. When air is allowed to percolate through many organic materials including coal then there will be a measurable rise in temperature. The same phenomenon can be observed in crushed sulfide ores and is caused by a progressive series of adsorptive, absorptive and chemical processes. These produce heat and an observable elevation in temperature. If the airflow is high and in a balanced equilibrium at which the rate of heat removal is equal to the rate at which heat is produced; the temperature will stabilize. The process will also reach an air-constrained equilibrium if the airflow is sufficiently low to inhibit the oxidation processes. However, between these two limits there is a dangerous range of percolating airflows that will encourage spontaneous heating. To control spontaneous combustion the usual process is to remove airflow from the gob areas and not have bleeder systems. This results in sufficiently low flows to inhibit the oxidation process. However, reducing flow has the disadvantage of increasing the concentration of methane gas. Where significant methane gas and spontaneous combustion are possible the use of nitrogen injection to control this gas may be the only method available to control both hazards.

In coal mine ventilation design, traditional conveyor systems have been placed in neutral airways to prevent the air used to ventilate these systems from actively ventilating the working faces.

However, with increasing production rates leading to higher gas liberation and elevated airflows, the conveyor entries have been used to provide fresh air to the working faces in conjunction with the fresh air entries. In order to use the conveyor air at the production face, the ventilation system requires bulkheads to separate the fresh air and conveyor air. This provides a dedicated fresh air escape way to be maintained from the working faces and a parallel route for the additional air capacity to reach the working faces. In addition to the physical separation, gas/smoke sensors are installed along the length of the conveyor systems to ensure early detection of conveyor fires and allow for rapid notification to underground personnel.

3. Conclusions

As new ventilation technology emerges we must not lose focus on the basic principles. The use of ventilation modeling software represents a significant time saving tool and can greatly assist the ventilation engineer in developing complete and thorough designs, allowing for the rapid development of numerous permeations and design options. However, the ventilation engineer should never lose sight of first principals. The tools available to the ventilation engineer are only as good as the project inputs developed by the engineer.

Technological advances in monitoring and control systems have made the implementation of VOD systems a reality. However, they must be properly designed such that safety is not sacrificed in the search of increasing efficiency and decreasing power and infrastructure costs. Developing and installing monitoring systems has increased the level of safety by allowing continuous monitoring of gasses and temperatures throughout the mining areas. This allows the mine to evacuate or receive notification when adverse or dangerous conditions are encountered. The continued advances in ventilation technology will help to elevate the health and safety of the miners, as long as the ventilation engineers do not lose perspective of the founding principles of ventilation.

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