Chapter 16
Energy-Efficient Mine Ventilation Practices

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Abstract Energy efficiency in mine ventilation, which is responsible for a substantial amount of total energy consumption, is of paramount concern in underground mining. Achieving energy-efficient mine ventilation practices is not only important for reducing total operating and energy costs but is also potentially the most effective means of reducing greenhouse gas emissions and environmental and occupational health and safety. This chapter presents a comprehensive review of the literature on energy-efficient mine ventilation practices and approaches to provide the current knowledge and research frontiers on energy efficiency in mine ventilation. Successful case studies, which resulted in efficiency increases, are also included to illustrate already existing energy efficiency alternatives and energy-saving opportunities. This review is expected to provide mining professionals a tool for improving current operations and achieving best practices.

Keywords Mine ventilation · Energy efficiency · Mine fans · Power consumption
Ventilation optimization

16.1 Introduction

Energy efficiency can be defined as decreasing energy consumption without sacrificing an ultimate product and/or service. Increasing scarcity of energy resources and escalating global environmental problems necessitate adapting energy-efficient practices especially in energy-intensive industries such as underground mining, since energy efficiency is potentially the most effective means to reduce energy costs and greenhouse gas emissions.

In underground mining, mine ventilation is responsible for a substantial portion of total energy consumption. Costs incurred because of ventilation may range from

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20 to 40% of the total energy costs and energy consumption in ventilation may reach 50% of the total energy consumption [1]. Papar et al. [2] estimated annual energy consumption for underground mine ventilation systems in the U.S. to be approximately 43.2 TJ. This amount is equal to about 3.5% of total energy used for lighting by the residential sector and the commercial sector in the United States in 2015 [3]. Du Plessis [4] claimed that every one percent saving on the ventilation and refrigeration energy costs amounts to US$80,000 per annum (at US ¢ 1.39×10^{-6} per J corresponding to US$0.05 per kWh). Considering this level of energy consumption, increasing efficiency of energy use associated with mine ventilation has become an emerging issue.

Achieving energy-efficient mine ventilation practices is not only important for reducing total operating and energy costs but also potentially the most effective means of reducing greenhouse gas emissions for underground mines. This is especially important given that recent policy initiatives dictated by several governments force industry to pay carbon taxes and other penalty costs for carbon emissions [5]. Unfortunately, experience has indicated that majority of existing ventilation systems have efficiencies of 65% or lower [1]. Increasing energy efficiency and adopting energy-efficient mine ventilation systems require systematic planning, optimized designs and their careful implementation to ensure maximized energy efficiency, minimized loss, and confirmed health and safety requirements.

There have been research-based case studies and industry practices for improving energy efficiency in mine ventilation. It is important to understand the current knowledge in order to achieve the best practices and propose pathways for future action. The goal of this chapter is to present a review of the literature on energy-efficient mine ventilation and propose future research directions. The chapter is organized into five main sections including this introductory section. Other sections include a discussion of the main elements of mine ventilation, mine ventilation efficiency improvement areas, some of the ventilation efficiency improvement strategies, and recommendations for future research and developments. This review is expected to serve as an essential tool for mining professionals who desire to improve their operations and achieve best practices with respect to energy-efficient mine ventilation.

16.2 Mine Ventilation Fundamentals

Mine ventilation, as part of total air conditioning, can be defined as creating an artificial atmosphere in underground mines to sustain workers' health and safety and to keep mining operations running continuously. The objective of mine ventilation is to provide airflows in adequate quantity and quality to dilute contaminants to acceptable levels in all parts of the mine where personnel are required to work or travel [6]. The significance of a carefully designed ventilation system is not limited to meeting regulatory and organizational health and safety requirements for workplaces. It is also required for operating diesel engines and blasting.

Mine ventilation air or fresh air is sent to the mine using mechanical ventilation fans. The magnitude and direction of air are controlled by regulators and fans through mine airways. The energy input to the fan should be high enough to overcome the mine resistances and to create sufficient pressure so that the mine air can reach the desired underground working areas. The basic fundamental formula to find the required pressure to be supplied by the fan is given by the square law as in Eq. 16.1 [7].

$$P = RQ^2 \tag{16.1}$$

In Eq. 16.1, P (Pa) is the required pressure difference to be supplied by the fan, R (gaul) is the mine resistance, and Q (m^3/sec) is the required amount of fresh air. Mine resistance is a function of friction (K), length of the airway (L), and size and shape of the airway as given by Eq. 16.2, in which C is the perimeter of the airway and A is the cross-sectional area of the airway. Mine resistance in SI unit is expressed as gaul [7].

$$R = \frac{KCL}{A^2} \tag{16.2}$$

Air power, which is the required power to create the desired pressure difference for a particular amount of air, is given by Eq. 16.3 [7].

$$\text{Air power (kW)} = \frac{P \times Q}{1000} \tag{16.3}$$

The fan input power, which is higher than the air power, is what should be supplied to the system in order to compensate for any losses in the system. The ratio of air power to fan input power is called as fan efficiency (Eq. 16.4) [7].

$$\text{Fan efficiency (\%)} = \frac{\text{Air power}}{\text{Input power}} \tag{16.4}$$

From above-mentioned principles, mine ventilation efficiency is related to mine design, fan and quantity-related factors. Design parameters such as, length of the airway, size of the shaft, and size of the airway are dictated usually by mine design features which are not quite flexible once operations begin. However, the planning and design of mine airways are critically important as they influence the pressure drop between inlet and exit, which further affect required air power and efficiency. Efficiency is directly proportional with pressure loss.

The air power is shown to be proportional to both the head loss and the air quantity. However, head loss in turn is proportional to the square of quantity (Q^2), resulting in the power being proportional to the cube of the air quantity.

This relationship between power and air quantity shows that quantity is the most important factor that influences air power. Therefore, in an effort toward improving the ventilation efficiency, air quantity should be cautiously considered during design and implementation of mine ventilation.

It is also important to recognize influence of fan laws, which dictate the relationship between fan power and ventilation parameters such as, flow rate, fan speed, and fan pressure, in studies targeting higher ventilation efficiency. Some of the relevant fan laws are [2]:

(i) Air flow rate is directly proportional to fan speed.
(ii) Fan pressure varies with the square of the fan speed.
(iii) Fan power is proportional to the cube of the fan speed.

A great emphasis should be placed on fundamental ventilation design principles, and fan laws to accomplish ventilation efficiency improvements. For example, Papar et al. [2] claimed that 10% reduction in fan speed will result in a 27% reduction in fan brake horsepower requirements.

16.3 Mine Ventilation Efficiency Improvement Areas

Mine ventilation is a complex optimization problem with various constraints and controllable and uncontrollable variables. Therefore, an optimized ventilation system requires careful planning and design. It is not that easy to alter designs once the implementation begins. For instance, once the shaft size is determined and driven based on the defined diameter, it will remain as it is. Therefore, increasing ventilation efficiency starts with the design and planning.

Knowing the fact that none of the designs can produce the best solution unless it is implemented properly, installing and operating main and auxiliary ventilation units and maintaining them with utmost care are of paramount concern for ventilation engineers. Therefore, in any attempt to improve ventilation efficiency, emphasis placed on the whole system starting from the design stage to the final output.

Various strategies have been proposed by researchers to improve mine ventilation efficiency. These improvement areas and techniques are grouped into two main groups: (i) efficiency improvement techniques related to modeling and design of ventilation system; and (ii) efficiency improvement techniques related to implementation of the designed ventilation system.

Importance of ventilation modeling and utilizing computer simulations to optimize ventilation systems are emphasized by the following advantages: [8]:

- *Economic sizing of main airways using ventilation modeling*: Engineers can simulate different airways of various sizes to estimate the associated ventilation economics and determine the optimum size of airways which yield the loweset overall cost.

- *Application of on-demand-based ventilation and on-demand-based heating and cooling control*: Ventilation models provide a fully dynamic simulation platform where airflow can continuously be changed and balanced based on the projected equipment moves, mining progress and air conditioning requirements. Mines can achieve optimized airflow splitting resulting in an minimized reduction in wasted air.
- *Intelligent active ventilation system control*: This system uses live modeling and online monitoring to allow for real-time evaluation of the underground environment and can be used to provide ventilation flow control to minimize fan power costs.
- *The application of main fan energy management, with reduced air flows during selected peak and off peak periods, resulting in substantial reduction in peak power demand*: Optimization models such as genetic algorithms can be utilized to determine the most effective combination of the fan operational duties, periods and and locations to minimize the operational fan power costs.

Moreover, a number of areas in improvement of energy efficiency of ventilation systems have been addressed. These are:

- Retrofit of main fan installations
- The use of variable pitch axial fans that can be adjusted down during periods of low activity
- The use of variable speed drives to provide speed control, reduce mechanical stress on the fan and motor and reduce energy consumption
- The upgrading or replacement of an impeller with a design impeller to suit the actual ventilation requirements, resulting in increased fan efficiencies
- The use of composite materials (lighter than steel, with higher resistance to fatigue) limiting fan impeller and blade failure.

16.4 Some Ventilation Efficiency Improvement Strategies

16.4.1 Mine Ventilation Overall System Optimization

In mine ventilation, mine air is supplied by ventilation hardware system which is mainly composed of power supply, motor, coupling, fan, flow control devices, ducts, and passageways [2]. Usually, fans are considered as the most important component of the system to improve the efficiency, however, as suggested by Papar [2], overall system approach should be adopted and mines should seek overall efficiency [2]. It has been reported that the power consumption of ventilation fans may account for up to 25% of total power consumption in a coal mine, but the average efficiency is only 57% [9].

It is also important to recognize that dampers, vanes, elbows, and other directional changes in the ducting systems have significant impact on fan performance

Fig. 16.1 Ventilation hardware system components [2]

and the energy efficiency of the mine ventilation system [2]. Du Plessis also claimed that reducing the operating costs significantly requires overall system optimization in addition to appropriately designed, energy-efficient equipment single ventilation and cooling components [10].

Focusing on individual efficiencies may lead to incorrect conclusions about the system efficiency. Similarly, life cycle of the system should be assessed rather than focusing on the short-term needs and solutions associated with them. Typical ventilation hardware system is presented in Fig. 16.1 [2].

Figure 16.1 shows that although the individual component efficiencies for the motor, belt drive, and fan are relatively high, the overall system efficiency is just 27% due to the fact that the pressure losses associated with the outlet damper control contribute significantly to the overall system performance [2]. This example clearly validates that using a systems approach instead of a component-based approach is critically important in considering potential efficiency improvement alternatives [2].

Papar and colleauges [2] conducted a case study in a gold mine requiring 141,000 cfm of air with the two existing axial-flow fans. However, they were not providing enough supply air into the mine because of the following reasons:

- The two fans had been mounted only inches apart from each other directly on the shaft bulkhead. No provision had been made to install outlet cones on the fans which would have allowed the proper development of flow and pressure before the air was dumped swirling into the mine shaft.
- The fans did not have inlet cones. This omission increases inlet losses and results in a poor flow profile into the fans.
- The fans were installed inside a heater house. Due to the configuration of the heater and the entry into the house, the air had to make a 90 turn just before the fan inlets.
- System performance tests indicated that the mine resistance was approximately 20% higher than design.
- A gap in the shaft collar was allowing approximately 4000 cfm to escape at the bulkhead.

Based on the field study, it was established that the two existing fans are able to meet the requirement of 141,000 cfm provided that a proper aerodynamically designed duct system was installed. This was completed and once the new inlet cones were installed, it was found that the reconfigured system met the 141,000 cfm airflow requirements. The cost of the new ductwork, inlet cones and relocation work was approximately $60,000. The streamlined arrangement resulted in an avoided horsepower increase of over 300 hp. The savings on this avoided energy use are approximately $112,000/year [2].

Minimizing various losses involved in fan system can improve efficiency, which in turn facilitate savings in energy consumption. Fan efficiency is greatly dependent on the profile of the blade [11]. Panigrahi and Mishra [11] conducted Computational Fluid Dynamics (CFD) simulations of drag and lift coefficients of six different airfoils using the ANSYS Fluent software to help with the selection of an energy-efficient blade profile for mine ventilation fans.

Another method of efficiency control is variable pitch angle in motion fans. The blades on axial-flow fans will adjust to meet the changing system requirements while in motion which assists in achieving higher efficiencies [2]. The fan manufacturers may be able to modify the fan by deblading and removing fan blades [12]. Power intake could be minimized by selecting angle of blades and rotation velocity of the fan at the pre-set minimum depression levels [13].

De Souza [4] presented case studies conducted to reduce power consumption, to lower operating cost, and to increase ventilation efficiency. In one of the case studies, two surface exhaust fans operating in parallel were inspected and surveyed. The fans have a diameter of 2.1 m and hub diameter of 0.8 m and they had 261 kW motors operating at 1170 rpm. De Souza [4] claimed that although fan assemblage was well designed with acceptable resistance pressure losses, the fans were fitted with very inefficient cones which were 1.5 m long and 2.4 m in outlet diameter. The cone losses were estimated at 0.161 kPa, the fan velocity pressure including losses was 0.41 kPa and the total pressure was estimated at 1.9 kPa with operating power per fan was calculated to be 230 kW.

The existing system was modified by replacing existing exhaust cones with more efficient cones of 4.3 m long and 3.05 m in diameter. With this new configuration the cone losses were reduced to 0.149 kPa. The new fan velocity pressure including losses and the total fan pressure were estimated as 0.25 and 1.74 kPa, respectively. The operating power per fan was reduced to 211 kW. Therefore, the total operating power savings are 38 kW and the annual savings in operating cost is $37,330 based on a power cost of $0.112 per kWh [1].

In the same underground mine, another modification on fan operation yielded a decrease of 22% in annual operating cost. The previously utilized booster fans of 1.67 m in diameter and 0.66 m hub diameter had 112 kW motors installed operating at 1200 rpm. The blade settings were 20°. The fan was a higher pressure fan, however, because of the low system resistance they were deemed to be operating inefficiently [1]. In order to improve the efficiency without incurring any additional investment cost, the fans were operated in half-blade and with a blade setting of 22°. In doing so, the fans supplied the same required flow but with an increased efficiency of 59.5% and decreased annual operating cost of $117,470 which used to be $150,000. These two case studies showed that modifying fan configuration may result in significant improvement in the ventilation efficiency.

In a deep underground mine in South Africa, energy savings of 10,400 MWh per annum were achieved, resulting in an energy cost saving of US$2 million per annum, by changing the inlet guide vane setting of the main surface fans. It would be possible for the mine to save an additional 3300 MWh and effect a further energy cost saving of US$0.5 million per annum by stopping an underground booster fan. The main penalty attached to these changes is that the underground airflow would be reduced by nominally 7% [10].

16.4.2 Auxiliary Ventilation

In order to increase the efficiency of mine ventilation, auxiliary ventilation, and auxiliary equipment stations could be utilized where necessary. There are various devices and auxiliary ventilation arrangements to ventilate dead-end openings such as check curtains, line brattice, jet fans, injectors, diffusers, scrubbers, booster fans, spray fans and vent tubing [7]. The well-designed auxiliary ventilation system not only provided supplemental flow to assist main ventilation system but also increase the effectiveness of dust and gas control. A case study conducted in a long wall mine revealed that effective utilization of auxiliary facilities could save significant amount of air [14]. In the study conducted by Kazakov et al. [13], transferring a part of the main fan load onto additional draft sources located nearby difficult-to-air sites that partially reuse the site return air allowed energy saving in ventilation [13].

In an attempt to improve mine ventilation efficiency, it needs to be ensured that installation, inspection, and maintenance of auxiliary ventilation system and its components are done properly and any cause of inefficiency in the system should be investigated. A case study conducted in an underground hard rock mine showed that improving an improper auxiliary ventilation system with improperly hung fans, leaky duct-to-fan connections, and damaged ducts, the ventilation efficiency yielded a reduction in cost by 51% [1].

16.4.3 Ventilation on Demand

Since air is a costly commodity in mines, ventilation on demand [15] principles, although it still is not commonly implemented [4], should be applied. Ventilation on demand can be described as supplying sufficient amount of air where necessary and when necessary rather than keeping constant airflow quantities at all times. Keith et al. [16] described ventilation on demand as supplying airflow to only working areas of the mine while minimizing airflow to remaining areas. It is applied to metal/nonmetal mines and not coal mines. While applying ventilation on demand principles, all the risks should be assessed in advance and no health and safety-related issue could be jeopardized.

One of the other strategies for energy saving is redistribution of air flows by backward control devices given their optimized location and selected values to fit the minimum main fan depression sufficient to ensure the required air flow [13].

System energy efficiency is achieved by operating mines at optimum airflow quantities and cooling capacity, and by cyclical and on-demand operation [10]. De Souza claimed that application of ventilation on demand may result in reduced energy usage by 20–40%. The results of some of the field studies have shown that a fully automated ventilation on demand system can have an electric power savings of up to 50% over the conventional mine ventilation systems [16].

16.4.4 Leakage Control

Another important issue that needs to be addressed for efficient mine ventilation is leakage; that is, unintended losses of mine air from intake to the return. Quantity of air, even if it may not increase, could be maintained by preventing leakage. In coal mines, leakage may reach up to 80% of the total volume of air circulated. Leakage may occur through stoppings, overcasts, and doors and also through crushed pillars and improperly packed gob. The leakage should be estimated precisely to determine the required air quantity at the fan inlet and should be kept minimal as it is the most common cause of inefficient distribution of air in mines.

In order to project the route of leakage, Zang and colleagues [17] used coal and rock permeability and pressure gradient between nodes of a ventilation network and developed pressure gradient matrix for a hypothetical ventilation system [17].

NIOSH [18] claimed that leakage could be best minimized by reducing the number of ventilation structures. This can be accomplished by lengthening the distance between crosscuts to minimize the number of stoppings per unit of development [19].

In a case study conducted in an underground hard rock mine, where push system with primary surface fresh air fans installed, 42% leakage amount was reduced to 9.9% by sealing off and shotcreting all bulk headed raise connections and installing appropriate doors. The reduction in leakage by 30.1% resulted in 64.4% savings in an annual fan operating cost of $370,160 [1]. Figure 16.2 shows the fan operation characteristics before and after leakage control. A 10% reduction in leakage may yield 30% reduction in the overall operating cost [1].

16.4.5 Load Clipping

Du Plessis [10] discussed energy-saving methods and strategies and as one of the options the authors suggested load clipping (energy use is reduced for certain parts of the day). If it is applicable for the mine schedules, the implementation of the ventilation and cooling system might be done during the time of the day when there are no personnel in the production zones. However, since the conventional approach to mine ventilation is to ventilate and cool the entire mine all of the time, this approach may not be suitable for every mine. In South Africa where power

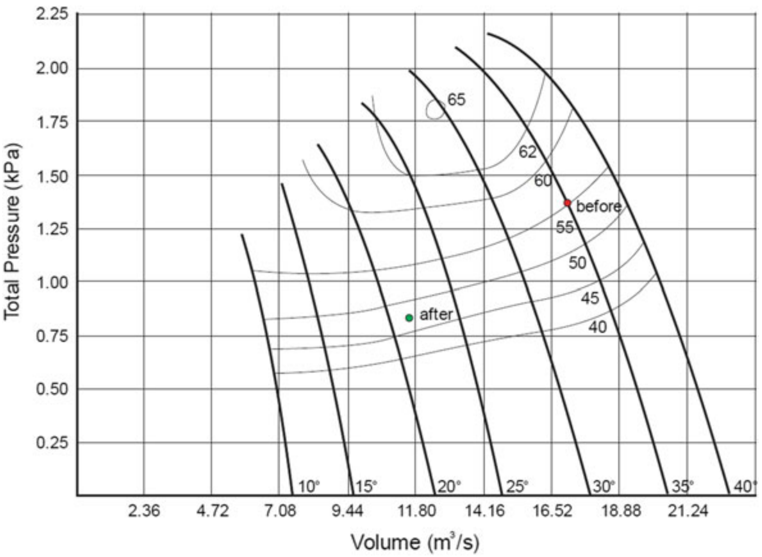

Fig. 16.2 Fan operation before and after leakage control [1]

tariff structures vary throughout the day and week, in most of the deeper underground mines, load clipping is implemented using inlet guide vane control to reduce the load during periods of peak power demand [10].

Mines utilize ice as an energy-saving strategy to reduce the amount of water circulated and to save on pumping energy. Ice is produced as either hard ice or ice slurry. Both are difficult to transport to where it is used and needed. This problem has largely been solved with the development and use of pipe conveyer belts [20]. In some South African mines, significant power savings are attainable using previously produced ice blocks at refrigeration plants during the low electrical demand periods and at a lower price and melting these ice during high electrical demand periods [16]. Impact of hard ice use for refrigeration and cooling was investigated by Mackay et al. [21] and concluded that it is a more attractive approach at lesser depths.

16.4.6 Underground Shop Air

If the quality of shop air is good enough to be reused in the mine, then routing of the underground shop air can be utilized to increase the mine airflow quantity [18]. In order to reuse the shop air in underground mines, the content of the shop air should be analyzed and contaminants should be determined. Mine ventilation engineers need to ensure that the risks are managed and all regulatory and organizational requirements are met prior to employing shop air. A case study conducted by NIOSH [14] revealed that use of mine shop air has a potential to improve the efficiency of mine ventilation by increasing the mine airflow. In this study, mine production areas of an underground room and pillar mine in which mine level airflows were 236 m^3/s and shop airflows were 24 m^3/s were provided with additional 19 m^3/s air saved out of 24 m^3/s and total mine airflow and subsequently efficiency is increased.

16.5 Recommendations for Future Work

Future research initiatives and case studies toward improving ventilation efficiency are critically important for two reasons. One is that increasing energy and electricity cost is one of the largest cost component in underground mining and any energy-saving option increases the economic success of mining projects. Further, it contributes to sustainability of the mineral industry even when commodity prices are low. Second, and more important, the benefit of such studies is to decrease the environmental burden of energy-intensive mining operations as the pressure to lower CO_2 and other greenhouse gas emissions is increasing. In addition to these benefits, efficient ventilation systems result in reduced maintenance costs and downtime, increased reliability and productivity, and improved work conditions [2]. Therefore, mine ventilation engineers should seek for energy-saving alternatives and more efficient ventilation systems.

Existing mine ventilation systems should be assessed and any inefficiency caused by improper design and implementation should be removed from the system. Optimum ventilation systems should be designed using computerized simulations and implemented with the view of overall system efficiency and life cycle costing principles. For the last decade, CFD analysis has been in use for large and complex ventilation systems in three dimensions. While it is important to recognize the benefits of using computational tools, the representativeness of models, the limits of programs, and accuracy of the results should be well analyzed through proper assessments, which requires experience and expertise.

Moreover, the general belief that “supplying more than adequate air does not harm” [2] should change. Ventilation on demand principles should be adopted where applicable and safe. Continuous monitoring of concentrations and locations of contaminants, harmful gases and particulates, is essential. Methane drainage systems might be utilized to remove the explosive methane gas in advance of operations and even converting it to an energy should be implemented where technically and economically feasible. Methane drainage also decreases the essence of ventilation requirements while increasing the potential energy sources.

In the future, the industry is expected to use more powerful information technologies as Wi-Fi, Bluetooth, tablet, smart phone and smart watch applications that allow engineers to communicate in real time to monitor air quantity and quality, exact location of contamination, etc. Virtual reality can also be utilized to simulate certain ventilation problems or recreate mine ventilation related accidents to manage the risks if available.

16.6 Summary

Energy efficiency in mine ventilation, which is responsible for a substantial amount of total energy consumption, is of paramount concern in underground mining. Achieving energy-efficient mine ventilation practices are not only important for reducing total operating and energy costs but also potentially the most effective means of reducing greenhouse gas emissions.

Significant energy savings are attainable by adopting integrated ventilation efficiency strategies. Ventilation engineers should be motivated, in the design and implementation of ventilation and cooling systems, to ensure efficient and optimized systems.

This chapter presents an overview the current ventilation efficiency improvement studies and successful case studies to help mining professionals toward improving the current operations and achieving best practices.

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