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MINERAL MINING TECHNOLOGY

Energy Saving Techniques for Ventilation Fans Used in Underground Coal Mines—A Survey[1]

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Abstract—As the energy consumption to operate a ventilation system is 25to 50% of the total energy requirements of an underground coal mine, proper planning, redesign, implementation and maintenance are necessary to achieve energy saving in this potentially viable area. Many researchers all over the world are therefore busy with solution for optimizing the consumption of energy in ventilation system. In this paper, the energy saving possibilities is discussed from different angles and a survey of current research is presented particularly on potential for electrical energy cost saving by implementation of various new technologies/methods. Ventilation demand in coal mines may vary throughout the year and by designing/developing a good ventilation system can not only minimize the cost of energy for the fan but also try to create healthy environment in mine. A number of recent commercially available systems are also reviewed in the paper to get the proper understanding.

Keywords: Mine ventilation, optimization of airflow, ventilation-on-demand, energy-saving, variable frequency drives (VFD).

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INTRODUCTION

Mine ventilation system plays an essential role in underground coal mines, when deep underground mines generate one of the most dangerous working environments for humans. The presence of methane and coal dust in the mine produces a risk of explosion. Thus ventilation has always been a matter of concern in underground coal mining. Proper planning, design, implementation and maintenance of ventilation system are necessary to achieve energy efficiency in underground coal mines. However, requirements of ventilation system change as the mine operation expands continuously by new developments and new methods.

Traditional mine ventilation system used to operate constantly during mining operation. As a result, it would consume more electrical energy making it an expensive affair in mine production. Development of cost-effective, reliable, maintenance-free and energy-saving techniques is therefore essential today as the cost of electrical energy is being increased day by day.

The performance of the entire coal mine ventilation system depends on three factors:

- Atmospheric condition in mine;
- Design of the fan;
- Power consumption.

Optimization of energy consumption and cost is possible by considering the above factors.

Atmospheric condition in mine plays very important role in every mine. Energy consumption in fan applications follows the fan laws [1]. These laws are used to calculate the operating performance of a fan when variables are changed. The commonly used fan laws are:

1. Air quantity/flow (Q) is directly proportional to fan speed (N);
2. Pressure (H)is directly proportional to the square of fan speed $(N)^2$;

[1]The article is published in the original.

3. Fan power (P) is directly proportional to the cube of fan speed $(N)^3$.

From above three laws, it is clear that fan speed can be controlled by considering air pressure (i.e. inlet and outlet pressure), air flow inside the mines. Selection of optimum operational speed of the fan can creates good and healthy environment in mine that will impact on mines productivity.

Next, fan designing is related with manufacturing. Fan performance and efficiency depend on the parameters like blade angle, number of blades, hub diameter, thickness of blades, corrosion and the material used for manufacturing blades, etc.

Finally, power consumption by motor/fan is one major factor in mines because the energy required to operate a ventilation system can be 25 to 50% of the total energy requirements of an underground mine. Therefore, suitable advanced techniques/methods are required to operate the motor like introduction of speed control methods, VFD techniques, intelligent control, etc.

Based on the above three factors, various techniques have been proposed so far for ventilation system along with many mine monitoring software, algorithms. The objective of the survey is to provide awareness to researchers about the recent developments and to invest knowledge towards more efficient and precise research. Many researchers are currently engaged in developing schemes that fulfil most of these requirements. This paper presents survey of methods and algorithms proposed thus far and the current trends in research for ventilation fans used in underground coal mines.

1. RECENT RESEARCH

Earlier, miners could easily travel in underground mines with normal source of fresh air from outside. As mines went deeper, underground explosions began to occur. In the 17th century [2], the source of the new danger was a mysterious gas called methane. Persons working in the vicinity of such ignitions were often killed by the force of the explosion to death. During the 20th century, increased stress on worker health, safety and the advent of new mining equipment and methods led to many changes in mine face ventilation practices. Mechanical ventilation became essential and was first accomplished by steam driven fans.

As a progress, these system improved with water sprays and scrubbers [3] mounted on the continuous miner are essential to the face ventilation system to direct the air up to the face to dilute and remove methane and repairable dust. Future research continuously find methods to improve the health and safety of underground miners by further reducing methane and dust levels in underground mine that improves mine ventilation fan performance and minimizes the energy consumption. Energy saving approaches reported so far can be divided into three categories which are discussed in the following sections.

1.1. Optimization of Airflow

Sui, J., et al. [4] discussed a new mine ventilation optimization and airflow control in underground coal mines. Based on the air distribution demand of the mine ventilation networks, the harmony search algorithm improves the performance. The improved harmony search algorithm enhances the convergent speed, used to find the global optimal solution of the network. After the optimization, the total energy consumption of ventilation system decreases.

Through Harmony Search optimized computation, the calculation of the air current control is done during coal mine fire. It is very important for rescuers to quickly make a correct decision during coal mine fire. The paper shows a theoretical approach to find optimum air distribution in mine when fire occurred in one branch. Though in real time application, fire actually occurs in more number of branches and the possible solution for this is not discussed in the paper [4].

In [5], researchers investigated an optimization model of the mine ventilation system network that takes the fan energy consumption as the objective function. By applying Harmony Search (HS) to the single-fan ventilation network, the ventilation system total energy consumption decreases up to 1640W, its rate of decline approximately is 1.94%. The total energy consumption of the multiple-fan ventilation network decreases up to 9396.5 W, the rate of decline approximately is 3.57%. It explained that HS overcomes certain limitations of the traditional optimization algorithm and has shown some good optimized result. This paper also shows a theoretical approach to find optimum air distribution in mine with single and multiple fans. Implementation and maintenance of multiple–fan system is costly.

In paper [6], Wei, G. recently introduced bionics-ant colony algorithm to solve the problem of mine ventilation optimization. In underground coal mines, the power consumption of ventilation system and the mining cost both are very high. The ventilation cost of one mine is different for the different layout of air roadways. So, it is very important to make the layout of air roadways optimal. Some kind of complicated combination of optimization problems have been proposed [7], which may be considered as air-path optimization problems.

The optimization of ventilation system may be divided into [8] two types—the first one is the optimization of internal adjustment of ventilation network and the second one is the optimization of the whole ventilation system. The authors concentrated on second optimization problem with a theoretical approach to find optimum airflow in mine. But authors did not consider factors like ventilation layout, pressure, resistance, mine area, etc.

In paper [9], Kozyrev, S. A. report the research results on the upgrading of the automated design planning of the underground mine ventilation system by using application of the genetic methods to analyse alternative ventilation systems at the design stage. This task can be explained by adjusting the distribution of air flows in branches of a ventilation system as a multidimensional and multiply-connected unit. The research data on the probability is presented to analyze and optimize ventilation systems by using genetic algorithms and other global optimization methods with case studies.

1.2. Fan Blade Designing

In paper [10], Bell, B. K. identifies mine ventilation engineering, in particular the electricity consumed by main fan units, as an area of potential energy savings. ‘Hermit Crab’ technique involves replacement of an impeller with a design impeller to suit the actual ventilation requirements, resulting in increased fan efficiency. New Hermit Crab impeller can be replaced when main fan is identified with lower efficiency and this can achieve the optimal operating point. This can be done by changing the blade aerodynamics, blade angles and/or blade materials so as to reach the desired operating point.

The flexibility of this concept enables one to define the optimal solution for the existing main fans. This retrofit can be achieved through shorter downtime and includes corrosion resistant impellers that provides improved air capacities and reduced energy consumption. In addition, in this paper, author explained some composite materials for blade manufacturing as well as use of variable speed drives (VSDs), ventilation on demand (VOD) systems and replacement of oversized motors. Specifications and measurements of new impeller and other mechanical parameters are not mentioned clearly in this paper.

Authors of paper [11] investigated that, afterrunning for a long time, fan impeller, air inlet, and fan casing of mine ventilation main fan are corroded seriously. Thus is a threat to safe operation of main fan, which increases running resistance and reduces efficiency. This design focuses on energy efficiency [12] and shows a substantial economic benefit in mine. Impeller corrosion structure generally is divided into three layers namely interface buffer layer, structural strength layer and surface layer. Control of thickness of each layer and physical and chemical performance index varies with case requirements. It is required to ensure that bond strength between anti-corrosion layer and metal base surface is greater than heat-induced peel strength between layers. This design uses zinc-rich primer coating that chooses epoxy resin as film-forming substances to prevent rust and corrosion. Zinc-rich primer coating is also known as electrochemical anti-trust paint because of its electrochemical protection of zinc to steel [13]. After anti-corrosion surface treatment, air volume is increased, which meets higher mine production and ensures mine safety. After anti-corrosion treatment, the on-site measurement is done and shown as Table.1, this study demonstrates manufacturing details of the fan impeller, but the techniques to avoiding corrosion are not mentioned.

Table 1. Main parameters comparison between using surface treatment and without surface treatment

Sl. no	Item	Without surface treatment	With surface treatment
1	Fan speed	490 r/min	490 r/min
2	Motor rotation	600 r/min	600 r/min
3	Motor rated power	1600 kW	1600 kW
4	Current	127 A	127 A
5	Negative pressure	4050 Pa	4050 Pa
6	Air volume	17872 m^3/min	17340 m^3/min
7	Input power	1308.39 kW	142307 kW
8	Power consumption	31415.3 kWh/day	34178.8 kWh/day
9	Voltage	600V	600V

Patel, J. S., et al. investigated different parameters affecting the performance of axial fan in underground mines [14]. Those are pitching angle, numbers of blade effecting the blower design, tip clearance, blade chord angle, erosion and corrosion of blades, reducing air gap etc. By changing pitching angle of the blade to 44, 54, 59, 64°, respectively, the value of air flow are 1175 CMH, 1270 CMH, 1340 CMH and 800 CMH. So, to increase flow rate, blade pitching angle should be kept around 59°. Increasing number of blades from one to two, results in six percent increase in aerodynamic efficiency. Again, by reducing the air gap between rotor tip and casing, it reduces the air losses and enhances the fan performance. But the paper presents factors affecting on axial fan without any mathematical calculations.

1.3. Modification of Electrical System

In paper [15] Chatterjee, A. et al. investigated the potential for energy/cost saving, by implementation of variable speed drives (VSDs) on ventilation fans. The objective was to minimize the cost of energy for the fan which is directly related to the fan's power consumption. This model also matches to certain constraints pertaining to the variable demand. Also, fan laws were integrated in the model to find the correct operating point of the fan driven by VSDs to obtain more realistic results, which is solved using the *fmincon* function in MATLAB**.**

This existing research regarding energy consumption in mine ventilation systems, focused on optimizing the flow distribution in the network such that the air power supplied by a fan is minimized [16]. This is achieved by modeling the network with use of graph theory and finding the optimal positioning of regulators to redistribute flow and result in a lower-rated required fan [17, 18].

The concept of ventilation on demand (VOD) is also introduced, the idea of which is to adjust a fan's speed over time (according to the required flow rate), as opposed to running the fans at full capacity at all times. It has been demonstrated in [19] that a small reduction in speed results in significant energy saving. This paper provides a foundation for further research which will consider factors such as multiple fans, leakages and efficiencies of the drives/motors, optimum air flow distribution in mine to save the energy consumption of fan by varying the fan speed.

Groza, V., et al. focused on energy saving at variable load by controlling the parameters of the power supply as a combination of variable frequency with reduction of magnetic loading of the motor in [20]. This method investigates the possibility of obtaining energy savings with big ventilation units equipped with variable pitch impeller mechanisms, driven by squirrel cage induction motors (SCIM). Variable impeller pitch mechanisms are used for big fan unitsin order to minimize theenergy consumption.

A mathematical model has been developed to estimate and maximize energy savings by fan affinity laws [21] and by using combined techniques. Energy savings have been estimated for every

Energy Conservation Measures (ECM), including reliability indicators estimation of the system impeller. This combination has an important advantage related to variable frequency drives cost. In this case, to drive 1800 kW motor, a VFD of 400 kW is required. Additional energy savings of 19% of the total energy consumption have been obtained. This paper shows a technical approach to minimize energy consumption for big ventilation fans at variable load by controlling electrical parameters.

In paper [22], researchers described a novel advanced diagnostic system with ventilationon demand capability that enhances through leaky feeders. To design a reliable and robust underground network has always been a challenge due to the special nature of mines. By considering dangerous and critical mine conditions, author introduced intelligence to the leaky feeder (LF) by adding a Diagnostic System (DS), made of two modes as shown in Fig. 1, one is Diagnostic Receiver Unit (DRU) connected to LF head end at the control room above ground and second is Diagnostic Transponder Unit (DTU) connected to every node in underground i.e. amplifiers, power supply unit (PSU), sensors/fans. Leaky feeder works in three modes, i.e. self-configuration mode, normal mode and interrupt mode.

Ventilation on demand has the advantage in mine as it will operate the mine ventilation fans depending on data collected from sensors attached to the leaky feeder. Sensors are installed in underground that keep track of the pollutant levels in air and whenever it reaches a certain threshold value, sensors will interrupt DRU resulting in the fans being turned on. Then during the normal mode when the DRU reads low or normal pollutant level, the fans can be turned off. It achieved huge power savings that will be reflected in the operating cost of a mine. This paper shows importance of communication in mine and clearly explained performance of leaky feeder in different modes.

In [23] Shonin, O. B., et al. focused on multi-purpose control system of variable frequency drive to minimize energy losses and to speed control of main fan. On the basis of simulation, drive energy losses in steady state mode of operation may be estimated through application of on-line iterative method [24, 25]. By applying an extreme of the energy loss function, it gives benefits of about 5-10% energy saving.

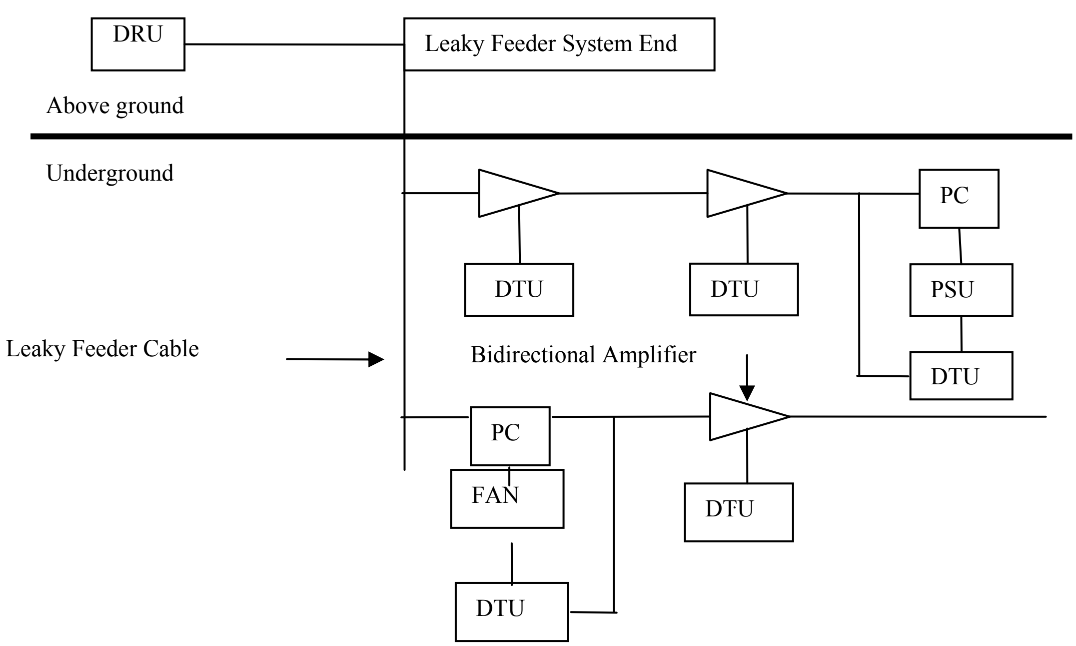

Fig. 1. Leaker Feeder Diagnostic system.

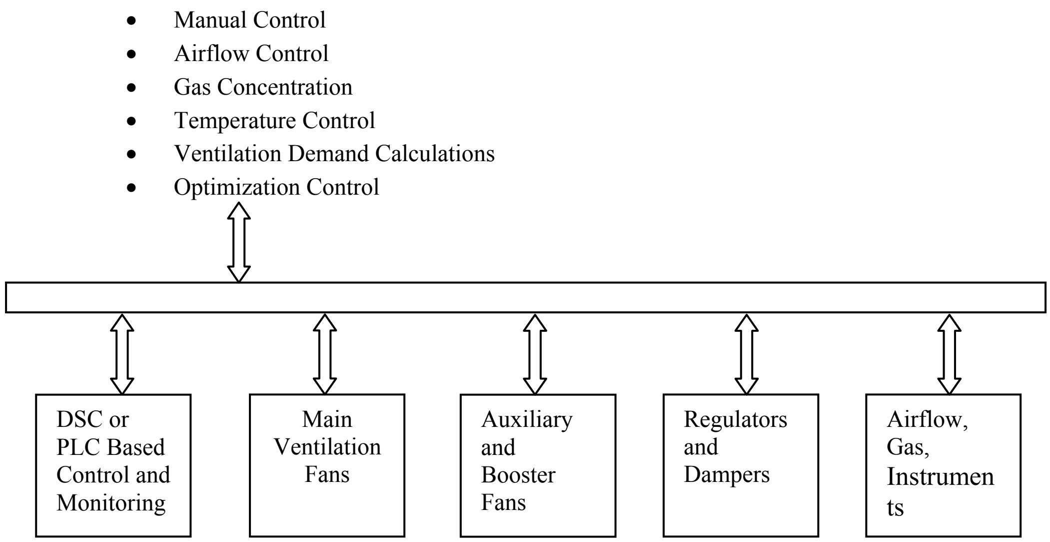

Fig. 2. Basic structure of Smart EXEC.

Speed control of main ventilation fan may be achieved with variation of blade angle and different operating points for centrifugal fan and axial fan. Also, the performance characteristics of centrifugal and axial-flow fans, various modes of operation have been investigated to confirm high efficiency in speed control. Combined control method is used for providing required air flow in underground mine. This paper presents possibilities of minimizing energy losses and improves the ventilation system efficiency.

2. COMMERCIALLY AVAILABLE SYSTEMS

Some of the latest developments in ventilation-on-demand (VOD) systems have been commercially packaged by companies such as ABB, BESTECH, and SIMSMART etc.

BESTECH, a leading provider of system automation to the mining industry in Canada, recently developed NRG1-ECO (Energy Consumption Optimization) product that combines hardware and software to manage many pieces of automated equipment in a mine. Allen-Bradley Compact Logix PACs, air-flow sensors, fans, and regulators are controlled by SLC Micro Logix PLC, Ethernet allows communication between the compact logix and micrologix controllers and SLCs. Power Flex 600-volt variable frequency drives (VFD) significantly reduce the energy used during fan operation by precisely regulating motor speed, and maintaining torque levels to match the needs of the load. This VOD system is contributing to an estimated $400,000 in energy cost savings per year, with initial connection to only 16 auxiliary fans [26].

SIMSMART offers [27] a real time solution in the mining industry, a complete SCADA system called Smart EXEC (Expandable Energy Control) that fully supports ventilation on demand. Figure 2 shows the basic structure of a smart EXEC, it optimizes ventilation energy savings up to 50%, health and safety benefits, production enhancement, and reduction in future ventilation infrastructure.

ABB, the leading power and automation technology group has launched its smart ventilation system that offers a real time analysis and control system to ensure safe working conditions and also minimization of energy-use by ventilation fan. ABB now offers another new unique method called Model PredictiveControl (MPC) [28]. Multivariable models describe how changes in the speed of fans affect both the airflow and the pressure. Gas concentration, air flow, speed and power of the fans may be controlled also.

CONCLUSIONS

Ventilation system is always plays very crucial role in underground coal mines. Ventilation requirements may vary throughout the year in mine, so it is mandatory to design efficient ventilation system, in most of underground mines considering all realistic aspects and difficulties in design. In most of the cases, the researchers did not test their system in real underground mines considering all the practical aspects. In this paper, different techniques, algorithms proposed so far all over the world, are discussed in the previous sections. Along with all the techniques discussed, implementation of demand controlled ventilation (ventilation on demand) employing variable speed drives (VSDs) may be considered as the most capable and promising method to save the energy, fulfilling the requirement of air flow in underground mines. It is observed from this review, most of the research works present theoretical approach to optimize the air flow and mechanical parameters effects on the fan performance. Only a few research works show the optimization of ventilation fan speed and energy consumption in mine.

In underground coal mines, atmospheric condition is continuously changing with the change of mine area and speed of the fan. Ventilation fan speed may be considered as the main factor to create and maintain healthy atmosphere in mine. So, the challenge of maintaining optimum air flow distribution in specific mine establishment by varying operational speed of the ventilation fan may be the future direction of research to manage the increasing energy cost.

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