Efficient use of energy in the ventilation and cooling of mines

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Synopsis

Escalating energy and electricity costs have become one of the largest drivers of expenditure in mining operations. Over the last eight years, energy costs have tripled when expressed as a percentage of total expenses in South African mines. In an effort to manage and reduce electricity costs, energy management strategies can be developed, inefficient operating units replaced, and the operation of energy-consuming components of ventilation systems optimized.

Power consumption on mines is controlled mainly by three strategies, namely *load clipping*, by which energy use is reduced for certain parts of the day; *load shifting*, by which energy use is shifted to other parts of the day; and *energy efficiency*, by which energy use is reduced permanently.

In this paper several projects that were implemented using the first two strategies of load clipping and load shifting are investigated. The actual and potential savings that can be achieved by implementing such energy-saving interventions are presented.

To reduce the operating costs of ventilating and cooling underground mines permanently, system optimization studies must be completed. Methods that can be used to reduce energy usage by optimizing cooling and ventilation systems are described, and network simulation models that accurately reflect the current and planned ventilation conditions are discussed.

These models are then used to examine various options for improving the overall ventilation and cooling strategy. Different optimization scenarios can be simulated, and this assists the design engineer in obtaining the most energy-efficient system that will satisfy design workplace conditions. The final outcome is a reduction in operating costs, which can result in better operating margins and an extension of the life of mine.

Keywords

energy, electricity costs, efficiency, ventilation, cooling, optimization, simulation, energy management, energy strategy, load clipping, load shifting.

Introduction and background

South African electrical power costs have traditionally been low by international standards. However, recent tariff increases and future projections of power costs have resulted in a significant rise in operating costs. Power tariff structures vary throughout the day, differ on Saturdays and Sundays, and change between winter and summer. The difference between the lowest and highest tariffs is as much as a 1 000% (Eskom, 2013). Although difficult to quantify, the cost of non-delivery of power will have an even greater effect on mine costs, productivity, and safety. Eskom (the South African electricity public utility) has attempted to alleviate the scarcity of electricity in South Africa by contacting and asking large users of electricity, including the mines, to reduce consumption, which could have an adverse impact on mine production.

Internationally, increasing electricity costs are among the largest drivers of expenditure in the mining industry and the reduction of energy use, and thus power costs, can assist in offsetting lower commodity prices and reducing margins.

Many of the larger corporations and mining houses have identified energy and the management thereof as a production and cost driver. One such study (Du Plessis and Van Heeswijk, 2012) showed that energy now constitutes over 20% of the mines' cost base. From this study, an integrated energy and carbon management strategy was developed to facilitate a holistic approach to managing energy and carbon emissions. It covered generation sources and the main fuel- and electricity-consuming assets, and considered mining methods and how they affect energy intensity. The strategy arrived at considered six key elements, namely:

- *Understand:* measuring, monitoring, and managing energy consumption and carbon emissions
- *Plan:* factoring energy and carbon emissions into operational and life-of-mine plans
- *Operate:* operating core assets more efficiently to achieve lower energy intensity

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- *Replace:* replacing carbon-intensive sources of energy with renewable energy
- *Invest:* spending now to reduce energy costs in the future
- *Enable:* addressing underlying factors that will enable the company to reach its energy and carbon goals.

All of these elements must be considered in the life-cycle design. Furthermore, it is important that mine ventilation and cooling systems operate as efficiently as possible to reduce capital requirements and operating costs, without compromising a safe and healthy working environment.

There are several stages during the design, implementation, and operation of mine ventilation and cooling systems where energy efficiency can and should be optimized. The initial stage is planning and optimization of primary variables for the proposed system. Next, individual system components are optimally designed, followed by the efficient integration of these components. Finally, energy efficiency is further improved during operation through cyclical control of systems and ultimately by supplying ventilation and cooling on demand. Any reduction of electrical power cost must be evaluated in relation to the effect on production and the overall mine operating cost per ton mined.

System optimization

Although it is important to ensure that single ventilation and cooling components (fans, pumps, compressors, *etc.*) are appropriately designed and energy-efficient equipment is procured, reducing the operating costs significantly requires overall system optimization. A typical ventilation system in a deep South African mine consists of downcast and upcast shafts, intake and return airways, and a main exhaust fan installed at the top of the upcast shaft. A typical cooling system includes a refrigeration plant producing cold water and heat exchangers cooling the mine's intake air by direct or indirect contact with the cold water. This strategy applies to current ventilation and refrigeration systems in operating mines, as well as to the designs of future operations.

System energy efficiency is achieved by operating mines at optimum airflow quantities and cooling capacity, and by cyclical and on-demand operation. For instance, large amounts of power are consumed by refrigeration equipment in the South African gold and platinum mining industries, with total installed refrigeration capacity of the order of 1 400 MWR. This relates to about 350 MWE of electrical motor ratings for refrigerant compressor drives, with motor sizes generally ranging from 0.5 to 2.5 MWE. In addition, the direct auxiliaries (cooling towers, condenser pumps, *etc.*) will have a total electrical rating of approximately 150 MWE, with motor sizes ranging from small to about 0.3 MWE. Thus, in the South African gold and platinum mining sectors, the total electrical nameplate rating for refrigeration equipment is about 500 MWE.

The engineering and operation of these systems has evolved over some decades to the current state of the art and significant achievements in energy efficiency have resulted (Gunderson *et al.*, 2005). The integration of energy-efficient systems (pumping, ventilation, refrigeration, *etc.*) and ventilation-on-demand (VOD) is still not commonly implemented, and there is room for further improvement in future (Acuña *et al.*, 2014).

Energy saving methods and strategies

Power consumption on mines is controlled mainly by three strategies, namely *load clipping*, by which energy use is reduced for certain parts of the day; *load shifting*, by which energy use is shifted to other parts of the day; and *energy efficiency*, by which energy use is reduced permanently.

The typical South African mining cycle in hard rock mining consists of two eight-hour shifts per day, one mainly for drilling and charge-up and one for removing the broken rock from the production zone. The third eight-hour period is dedicated to blasting and the clearing of the blasting fumes and dust, which is normally done in the afternoon. Production zones are thus occupied for a maximum of 16 hours per day. Although personnel are underground during the blasting shift, they will be in intake airways around the shaft. The conventional approach to mine ventilation and cooling is to ventilate and cool the entire mine all of the time. This approach fails to exploit the cyclical nature of mining, diurnal variations in ambient temperature, and variations in the cost of electrical power, and does not allow load clipping or shifting tactics to be implemented.

This cyclical schedule is ideal for implementing the operation of an energy-efficient ventilation and cooling system, as there are periods of the day when there are no personnel in the production zones. Fan power and refrigeration can be reduced during these times in a structured way. The following main methods and strategies have been implemented.

Main fans

Major work has been done on the energy optimization of main fans in South African mines. In most of the deeper mines, load clipping projects are implemented where inlet guide vane (IGV) control is used to reduce the load during periods of peak power demand (Du Plessis and Marx, 2007, 2008). IGV control involves specially designed, adjustable vanes installed in the air stream entering the fan inlet. These static (angle-adjustable) vanes are used to generate a swirl of air in the direction of the impeller rotation. As the swirl is increased by changing the IGV angle setting, the performance capability of the fan gradually reduces pressure/volume and power curves. The fan's characteristic effect is that the operating point is moved down the system resistance curve, resulting in reduced power consumption (Figure 1).

Improving overall main fan efficiency generally involves entire impeller replacements or even entire fan replacements. This is required where main fans are operating far off their original design duty points, due to changes between the planned and actual mine resistance or wrong specification during design. This strategy is still fairly new in South Africa, but it has huge potential as the average efficiency of main fan stations is much lower than it should be. In addition, variable speed drives (VSDs) can be implemented on secondary ventilation fans and flow can be reduced during certain parts of the day and mining cycle.

Refrigeration

The first line of defence includes the optimization of the precooling towers. These systems cool the warm return water (from underground) to a point close to the ambient surface

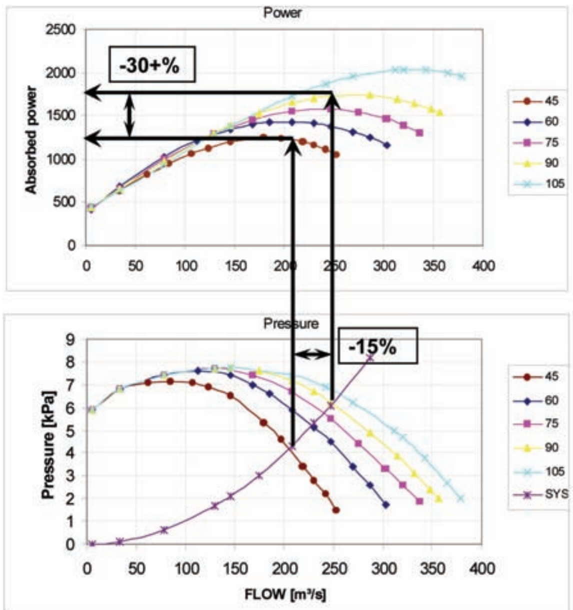

Figure 1—Fan curve showing operational points with IGV settings

temperature in direct contact cooling towers. This can account for a significant portion of the cooling required and is virtually free.

Conventional refrigeration machines are switched off during periods of peak demand, or thermal storage is used to store cooling for periods of high cooling demand (Roman *et al.*, 2013). In cooling systems, thermal storage that uses ice banks or water storage dams must be considered (Els, 2014). Ice banks produce ice on the outside of submerged heat exchanger coils during periods of low power cost and lower diurnal temperatures, and melt this ice during periods of high power cost and peak demand. Mine ice thermal storage also allows for power consumption profiling aimed at shifting the electrical load out of peak demand periods. Ice is produced during standard and off-peak power periods, and is subsequently melted by diverting water flow to the ice coils (Figure 2) to provide cooling during peak demand periods, thus reducing the load on all the water chillers.

Water mass is also effective for thermal storage because water has the highest specific heat of all common materials. In water mass thermal storage, the thermal capacity is dependent on the water mass and the temperature difference between the stored cold water and the returning warm water. In general, thermal storage will not be economical if this temperature difference is less than 5°C. However, in these mine applications this temperature difference is approximately 10°C. The fundamental feature of this storage is that it separates the cold and warm water volumes. One such system implemented at a South African gold mine was described by Du Plessis *et al.* (2005). This system uses ammonia refrigeration machines that cool water to 1°C. It consists of a warm water dam (18°C), a medium temperature dam (8°C), and a cold water dam (1°C).

Thermal stratification is the most common method of separating cold and warm water due to its simplicity, reliability, and low cost. In thermally stratified storage, the warmer, less dense returning water floats on top of the stored chilled water. The water from the storage is supplied and withdrawn at low velocity so that the buoyancy forces dominate any other effects. Water is most dense at 4°C and it cannot be stratified below this temperature. This approach has been used on a number of mines (Wilson *et al.*, 2005) (see below), but it generally requires tanks/dams with a minimum height-to-diameter ratio of 1.0 (Khalifa *et al.*, 2011).

Another method uses multiple compartments and labyrinth tanks. Pumping is scheduled so that one compartment is always partially empty for receiving return water, and water at different temperatures is thus stored in separate compartments. Labyrinth tank systems apply cold water and warm water at either end of a complex path through the dam and will generally have both horizontal and vertical traverses. The design commonly takes the form of successive partitions, with high and low ports.

By understanding the demand for underground cooling conditions in specific areas, control systems can be implemented on these units (Le Roux *et al.*, 2014). Any over-supply is inefficient and the goal is to control the cooling units to follow the demand. Besides fixing leaks in water piping, there are various ways in which energy savings can be obtained on the chilled water usage underground, such as:

- Controlling underground bulk air coolers
- Controlling underground cooling cars
- Installing isolation valves on the service water supply.

Saving potential

To provide a convincing argument for the viability of ventilation and cooling system optimization, it is necessary to look at the costs of providing ventilation, refrigeration, and cooling. Although these vary significantly from mine to mine, on a deep hot mine the costs can be as much as 15% of capital (US$200 million) and 25% of energy costs (*e.g.* 20 MW peak, 12 x 106 kWh/month for a large South African gold mine) (Gold Fields International internal data). The world-wide cost of power ranges from US$0.02 to US$0.10 per kilowatt-hour, with instantaneous peak rates being over US$0.20 per kilowatt-hour. Every 1% saving on the ventilation and refrigeration energy costs amounts to US$80 000 per annum (at US$0.05 per kilowatt-hour).

Figure 2—Ice storage dam

A case study example (Du Plessis and Marx, 2009) describes the development and implementation of a fan absorbed power control system using IGVs at a total of 23 fan stations (52 fans) between three mining business units (BUs). A target of 5.6 MW saving out of a 22.8 MW base load was set for BU 1, 7.5 MW saving out of a 30.0 MW base load for BU 2, and 7.4 MW out of a 25.5 MW base load for BU 3.

Fan absorbed power was measured at half-hour intervals and then analysed for the evening peak period (18:00 to 20:00) to determine whether the targets had been met. Performance should ideally be above 90% of target.

Figure 3 shows a graph of the actual load clipping achieved at BU 1.

The targeted and achieved power savings for BU 1, 2, and 3 were as shown in Table I.

The success of implementing IGV control to reduce airflow and save electricity is evident from the data presented in Table I, which shows that the targeted savings were achieved and exceeded.

Simulation for optimization studies

Ventilation and cooling system energy optimization generally includes the development of simulation network models that accurately reflect the current mining scenario and ventilation conditions. The calibration and verification of the predictions with measured environmental conditions are important to ensure a high level of confidence. These models are used to examine various options for improving the overall ventilation and cooling strategy, as well as for determining the effect of possible future changes. A number of scenarios, including different ventilation (fan/airway) and cooling (refrigeration/pumping) configurations, are typically examined to obtain the most energy-efficient system that satisfies the design and safe workplace conditions.

Network simulation software is specifically designed and developed to assist underground ventilation control engineers and practitioners in planning, designing, and operating mine ventilation systems. Interactive network simulation programs allow the simultaneous modelling of airflow, air thermo-dynamic behaviour, as well as gas and dust emissions in an underground mine. These programs cater for a wide range of mining methods and allow the rapid construction of simulation networks, thereby enabling online 'what-if' studies to be done to determine system requirements for optimal design and operation.

A typical integrated optimization system will consist of a properly calibrated mine model, as mentioned above, and an optimizer. The optimizer will generate different possible operational scenarios and pass these to the modelling package. The modelling package will model the mine and determine whether minimum ventilation and cooling standards are met. If this is the case, the specific combination of parameters is considered for control. This iterative process continues and the best combination of cost/operational conditions will be chosen for control purposes. By combining this process with time-differentiated set-points, an effective cooling and VOD system is implemented.

Typically, what-if studies are used to determine the optimal airflow quantity and cooling duty, and to reduce air leakage to a minimum. The system is then further optimized by determining the optimal positioning of ventilation and cooling infrastructure. Figure 4 is an example of a typical simulation network mine model.

In a case study (Hoffman *et al.*, 2012; Du Plessis *et al.*, 2012) conducted at a deep-level gold mine, a number of scenarios were simulated. After all the potential ventilation scenarios had been reviewed, the recommended optimized ventilation option was with the surface fans operating at

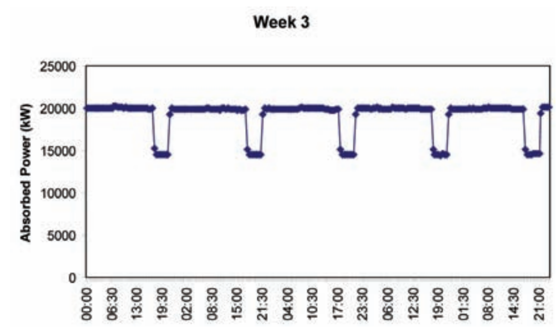

Figure 3—Measurement of absorbed power at BU 1

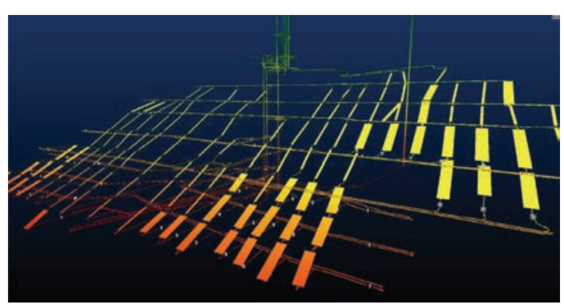

Figure 4—Simulation network model

Table I

Targeted and achieved power savings

Mine	Target			Achieved		
	Baseline (MW)	Savings (MW)	% of Baseline	Baseline (MW)	Savings (MW)	% of baseline
BU 1	22.8	5.6	24.6	20.2	5.4	26.7
BU 2	30.0	7.5	25.0	19.3	5.3	27.5
BU 3	25.5	7.4	29.0	24.5	7.1	29.0

20%, closed IGVs, and the stopping of some booster fans. Combined with this, the installation of underground refrigeration machines with energy-recovery turbines was recommended due to the shorter implementation time, lowest implementation cost, and least complexity.

The result of this study proved that, with careful planning, changes to current ventilation and refrigeration systems in deep-level mines can result in major electricity operating cost savings. At this particular mine, 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 IGV setting of the main surface fans. It would be possible for the mine to save an additional 3 300 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%.

Significant energy savings are attainable by improving refrigeration positional efficiency and reducing the volume of cooling water that is pumped from the bottom of the mine to the surface. Mackay *et al.* (2014) investigated the use of hard ice and concluded that hard ice as a refrigeration and cooling means has become more attractive at lesser depths.

Not only will this also allow greater flexibility, but the additional refrigeration and cooling water required for future mining will be produced by an underground plant, eliminating the need to pump 50 ℓ/s over 2 000 m back to the surface, and utilizing the existing two energy-recovery turbine stations. The total operational savings for this system will be approximately US$2.5 million per annum. The cost of the required modification will be US$8.5 million, with a capital payback period of just more than three years.

Conclusion

The rising costs of ventilating and cooling mines safely and efficiently dictate that operators have to implement optimized energy management and control strategies in mines. Ventilation-on-demand and cooling-on-demand strategies have the potential to reduce both the capital and operating costs of mine ventilation and cooling systems, and the mechanisms required are technically feasible.

From several case studies presented in this paper it is clear that a large financial benefit is possible through optimizing ventilation and cooling within a mine.

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