State-of-art ventilation and cooling design topics

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INTRODUCTION

Ventilation and cooling design has progressed in the past few years from a rule-of-thumb approach at a component level, to the art of balancing complete systems interactively. There is a high demand for ever-improved safety, health and productivity, and technology supply is being revolutionized with modern computing power and advancements in engineering. Because of the magnitude of the subject, it is difficult to write an all-embracive definitive paper and rather, this paper discusses a number of selected topics. Some of the most exciting developments have been in the area of software development, energy efficiency and energy management and the development of improved surface air cooler refrigeration systems. These topics are specifically discussed.

The concern over global energy resources has resulted in an increased emphasis being placed on energy efficient designs. In South African deep hot mines a main electricity consumer is the mine ventilation and cooling system. In this regard, a number of projects are being undertaken to implement energy efficient mine ventilation and cooling/refrigeration designs. These include new generation surface cooling installations that incorporate thermal storage management, active control and cyclical operation of ventilation and cooling systems, and systems in which in-mine ventilation parameters are monitored at a few strategic locations to predict conditions throughout the mine.

The design principles for energy efficient ventilation and cooling constructions apply to all of the design and operating stages. System energy efficiency is maximised by determining optimum design airflow quantities and wet-bulb temperatures, using innovative components, cleverly integrating already efficient components, and finally by cyclical and on-demand operation. The necessary knowledge and technology exist in most cases to drastically improve the energy efficiency, and it is a matter of applying sound principles from the design phase going forward.

ACHIEVEMENTS IN SOFTWARE DEVELOPMENT

Effective environmental control must take into account all influencing factors over the life of mine. These factors are complex and require planning and design to be continuously updated and optimised by using interactive design techniques. Simulation tools are used by ventilation engineers to ensure a balance between complex designs, and the practical operation of mine ventilation and cooling systems. The VUMA suite of simulation programs was developed to facilitate these designs and to verify, refine and incorporate practical operational parameters.

The VUMA vision is an interactive software suite catering for all the relevant sub-systems. At present this software suite includes VUMA-network: the ventilation [and heat] network simulator, VUMA-coolflow: the water distribution simulator accounting for thermodynamic interaction of the water and ventilation systems, VUMA-live: a simulator enabling real-time monitoring, VUMA-MineServ: software used to interact with mine scheduling software, and VUMA-chiller: the mine refrigeration plant process simulator. VUMA-transient, a subset of the vent/heat network, is used to simulate transient phenomena such as fan failures and cyclical or 'active' vent/cooling control.

Each of these tools uses a similar user interface and will ultimately be combined to be fully interactive. Currently the individual simulators are effectively used in system design and operation to reduce operating and capital requirements, optimise energy use and manage resources effectively.

ACHIEVEMENTS IN MONITORING AND CONTROL

It is often stated that, 'you can't control what you can't measure'. Due to the availability of improved instrumentation and communication systems, it is becoming easier for mine operators to monitor underground environmental conditions. However, the extensive number of airways and large range of variables and influencing factors make it impractical to locate remote instruments all over a mine. It is more practical to have a few critical measurement sites that are fully reliable and to use simulation software to extrapolate from this data to predict conditions throughout the mine.

The VUMA-network simulation software was recently improved to include a feature to incorporate critical measurements into the simulation network, which is then used to predict conditions throughout the mine. Software modules that were developed to enable this are capable of:

- Communicating between the mine monitoring system and VUMA-network
- Real-time solving and calibration of mine models
- Anticipating potential problems by displaying warnings when changes in measured parameters exceed specified limits.

By linking these software modules to VUMA-network the system increases the coverage provided by existing instruments through extrapolation of measured values to provide an expanded real-time view of the mine.

The concept of limited measuring points and prediction of the rest of the mine not only gives a real-time view of the complete mine ventilation network, but is also a powerful alarm system highlighting any abnormal conditions. Although the system is only used currently for monitoring, the ultimate aim is to provide a full network monitoring and control system.

ACHIEVEMENTS DRIVEN BY ENERGY EFFICIENCY CONSIDERATIONS

Large quantities of power are consumed by refrigeration equipment in the South African gold and platinum mining industry. At present it is estimated that the total installed refrigeration capacity is of the order of 1 350 MW_R on these mines. In terms of electrical motor ratings, this relates to about 350 MW_E in refrigerant compressor drives with motor sizes generally ranging from 0.5 MW_E to 2.5 MW_E. In addition, the direct auxiliaries [cooling towers, condenser pumps, etc] will have a total electrical rating of the order of 150 MW_E with motor sizes ranging from small to about 0.3 MW_E. Thus, in the South African gold and platinum mining industry, the total electrical name-plate rating for refrigeration equipment is of the order of 500 MW_E.

The engineering and operation of these systems has evolved over some decades and many highly talented engineers have contributed to the current state-of-the-art and much has been achieved in terms of energy efficiency. However, there still remains great potential to improve on energy conservation and energy management.

Electrical power costs in South Africa have traditionally been low by international standards and, until fairly recently, there has been a single overall tariff. However, future projections of power costs anticipate significant increases. Fairly recently, power tariff structures have been introduced that vary throughout the day, differ on Saturdays and Sundays and change between winter and summer. The difference between the lowest and highest tariff is about 1000% [see Figure X1]. The electrical power generation situation in South Africa is such that Eskom is providing incentives [through Government grants] to use power more efficiently and to shift power demand during critical times. Amongst these incentives, the Eskom program provides capital for projects designed to shift electrical power away from certain peak power demand periods. This capital is used for acquiring equipment and control systems to allow the energy shifting to be implemented. This has created the situation where there is a very strong awareness of energy related matters in mining. The energy efficiency issues in mine refrigeration can be categorized as follows:

- Cooling generation and distribution [including thermal losses, pipe insulation, energy recovery, losses in dams, efficiency of refrigeration machines, compressor speed optimisation, fouling, heat rejection efficiency, etc].
- Reducing mine heat loads [including issues such as backfill, tunnel insulation, mine layout design, mining methods, minimising diesel machinery, etc].
- Active cyclical control of refrigeration systems [including issues such as engineered thermal storage, thermal storage effects in cold rock, making best use of diurnal variations, mining cyclical activities, etc].

The following sections discuss the more recent considerations of active cyclical control, engineered thermal storage and ventilation and cooling on demand.

Cyclical control

Conventionally all areas of a mine are ventilated and cooled on a fulltime basis. This approach does not acknowledge mining as a cyclical operation, or cyclical changes in ambient conditions or variations in electrical power costs during peak periods. It is evident that the design of energy efficient ventilation and cooling systems requires new thinking in this regard.

The typical mining cycle in conventional 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 face blasting, normally in the afternoon. Mining crews in this case occupy the production zone for a maximum of two-thirds of the day. Although there will be personnel underground during the remaining third of the day, they will be in intake airways close to the main shaft. There is another shorter period between the two 'active' shifts where the production zones are unoccupied when shift changes takes place.

This cyclical schedule lends itself for energy efficient ventilation and cooling system operation. When production zones are unoccupied there is no need to continue supplying the normal air quantity and quality. It is therefore possible to reduce fan power and refrigeration during these times in a controlled manner. The design will require heat flow simulations to predict transient thermal effects and to ensure average thermal conditions remain acceptable. In addition, in practice it will be necessary to confirm that a reduced airflow quantity could clear all dust, gases and blasting fumes during the unoccupied period.

The active cyclic control of mine cooling systems has great potential for energy management and reduction of power costs. Again this is a very wide subject and the possible applications can be many and varied allowing limited examples of engineered thermal storage and cooling-on-demand to be discussed.

Example illustrating the benefits of cyclical operation of a bulk air cooler

The example relates to a 2000 m intake airway with airflow of 43 kg/s in rock with a virgin temperature of 50°C. Air arrives at a cooler at the start of the tunnel at 27°Cwb and is cooled down to 20°Cwb - a duty of 1000 kW. The temperature of the air at the end of the 2000 m tunnel is 26.7°Cwb. Figure X4 shows the effect on the wet-bulb temperature at the end of tunnel. The 1000 kW cooler is assumed to operate on a cycle of 18 hrs on and 6 hrs off. The original steady-state conditions [with 1000 kW cooler operating continuous] are shown as the horizontal reference line. Operating the same cooler intermittently causes the delivered air temperature at the end of the on-period [18 hrs] to increase to 27.2°Cwb. This is because the tunnel is now subjected to less overall cooling and will be slightly warmer. To fully compensate for this effect, additional cooling will be required during the on-period. This can be calculated as the additional cooling required at the end-point to achieve the original steady-state conditions. In this particular example this is 100 kW [43 kg/s from 27.2°C to 26.7°Cwb] – an additional 10%.

However the combined cooling of 1100 kW is only applied for 18 hrs which is 83% of the 24 hr cooling scenario. Figure X4 also shows that when the cooler is turned on again, the cold air arrives within 1°C of the temperature achieved at the end of the on-period [although it takes about 10 minutes to physically travel the 2000 m]. This delay is shorter than the travelling time for personnel to reach the same destination and should not be an inconvenience. It is also worth noting that the temperature at the end of the off-period using the air cooler in cyclical mode is only 2.5°C higher than the base-line. This is due, in part, to the cooling effect of the cold rock surface. Although the off-period conditions at the end of the tunnel are hotter than the on-period conditions, they will have little impact on the downstream cooling potential if it is timed to be after the blast and when personnel are not present. This is an important issue for the cooling of stopes and development sections immediately after the blast.

An alternative scenario is to achieve better on-period conditions by applying the original 24 hr cooling over the shorter 18 hr duration. In this particular example, the 1000 kW cooler becomes a 1330 kW cooler and the end-point temperature after 18 hrs drops to 25.6°Cwb - an improvement of 1°C, see Figure X5. This provides an additional 230 kW of cooling power with high positional and temporal efficiency. The maximum off-period temperature in this case will be 28.9°Cwb.

The above example demonstrates that the practice of cooling-on-demand can reduce the size of refrigeration machinery, reduce power consumption and/or improve conditions.

Thus the benefits of reducing overall fan power and refrigeration/cooling supply generally lie in the reduced absorbed electrical power. If a cyclical control strategy is adopted, the electrical power associated with ventilation and cooling systems can be reduced by about 20% for deep mines. These systems have to be carefully designed due to the increased safety risk and more demanding control and maintenance, as well as existing constraints such as diesel pollutant and blast fume removal and the provision of acceptable face velocities. However, operation is cyclical and therefore reasonably predictable and personnel and mining systems will adapt to it rapidly. Other studies, with the on/off control of underground recirculation based cooling systems, have indicated savings in refrigeration related power consumed of up to 20%.

Cyclical control of total airflow quantity can be achieved by using main fans fitted with variable inlet guide vanes [or in some cases variable speed drives]. Cyclical control of air cooling duty is easily achieved by using automated valves to change cooling water flow rates and/or temperatures. Conventional refrigeration machines could be switched off during these periods or thermal storage could be used to store cooling for periods of high cooling demand.

Engineered thermal storage

Thermal storage dynamics can be used to damp the effect of un-loading refrigeration plants at certain times – these thermal storage effects can be in the form of:

- Ice banks located in storage dams.
- Cold water in storage dams.
- Mechanisms that occur in the cold rock mass and the shaft steel work.

The engineered systems using ice-banks create, by far, the most powerful controlled thermal storage approach. However, where water storage dams exist, the practical convenience and economic factors make this approach attractive. The passive cyclical thermal storage in the static rock mass and shaft steel components can contribute a very useful and inherent effect, if correctly exploited both from the storage aspect [positive] and the thermal loss perspective [negative].

Cold-water dams in mines have been used for thermal storage for many years, however over time, the original control logic has often been lost. With the renewed strong current awareness of energy related matters the application of existing dams is coming under close scrutiny.

Ice thermal storage is well developed in industrial refrigeration utilities especially in so-called district-cooling systems. The concept is to produce ice on the outside of submerged heat exchanger coils during periods of low power cost and melt this ice during periods of high power cost and peak demand. Installations making and melting over 2000 tons of ice per day are common in North America and Europe. The schematic of a similar application that recently proved successful for mine cooling is shown in Figure X2 with a photograph of the ice formed shown in Figure X3. Although of similar design, the mine cooling application is significantly different when compared to the traditional district-cooling concepts. The differences lie mainly in the objectives of these systems. Mine cooling applications aim to produce 0°C water, which is used for efficient mine cooling. Another advantage of ice thermal storage systems is that refrigeration plants could be sized for average loads and these plants can then operate continuously at full load and therefore high efficiency.

X2 1B schematic
X3 pictures of ice

Mine ice thermal storage also allows for power consumption profiling and is well suited to the ESKOM Demand Side Management programme, which is aimed at shifting electrical load out of peak demand periods. Ice is produced during ESKOM standard and off-peak power periods and subsequently, this ice is melted by diverting water flow to the ice coils to provide cooling during peak power periods thus reducing the load on all the water chillers.

In terms of practical implementation on South African mines, one system has been operating for five years, another is under construction and numerous others are in the design stage. In these systems, a single refrigeration machine is operated on glycol and serves an ice-coil bank facility.

This use of ice in mine cooling systems differs from the current applications at ERPM and Mponeng where ice is the product transported into the mine for cooling purposes.

Ventilation and cooling on demand

Ventilation and cooling-on-demand has the potential to reduce both capital and operating costs of mine ventilation and cooling systems and the mechanisms required have proved to be technically feasible. These systems are generally more flexible than the cyclical systems described previously and entail supplying the necessary airflow quantity and quality as and when needed. As with cyclical control these designs have to cater for increased risk and demands on management and control.

Supply-on-demand systems operate on a concept of monitoring and controlling maximum air pollutant levels and wet-bulb temperatures. An example is secondary ventilation systems that are re-directed to follow the diesel fleet, reducing flow and cooling when the fleet leaves an area and increasing resources when the fleet enters another area.

In order to fully exploit this strategy it will be necessary to have a live ventilation monitoring system. VUMA-live can assist with the active control of ventilation and cooling systems as previously described. The system could identify whether operators are correctly switching fans on and off when they enter/leave an area, and it would be able to continuously assess whether sufficient air is being supplied to a working place. A central control station would be alerted whenever conditions do not satisfy minimum requirements. If the program is linked to a central vehicle despatch system then it would ensure that sufficient air follows equipment as it moves throughout the mine.

STATE-OF-ART OF SURFACE BULK AIR COOLING REFRIGERATION SYSTEMS

In recent years there have been significant developments with the strategy of surface bulk air cooling which have reduced both capital and operating costs. Surface bulk air cooling installations consist of refrigeration machines, air coolers, condenser cooling towers and interconnecting water distribution pipes. Recent developments have allowed these individual components to be assembled in efficient, economical and compact configurations. Developments in each of the major components and the overall system layout are presented below.

Refrigeration machines

The trend is to use standard packaged factory assembled refrigeration machines that have a proven record for reliability. These machines use a single-stage centrifugal compressor, shell-and-tube evaporator and condenser. The compressor-motor drive lines are factory assembled, coupled and aligned. The refrigeration machines use R134a refrigerant so as to reduce the health risks associated with a refrigerant leak. To summarise these refrigeration machines are robust and capable of operating over a wide range of duties at high efficiencies.

Condenser cooling towers

For a given cooling duty the absorbed power of the refrigeration compressors is dependent upon the condensing temperature and the condenser cooling towers are designed to achieve low condensing temperatures. The cooling towers are specified and designed to have good heat transfer characteristics and operate with a low water-air flow ratio.

The cooling towers are constructed in reinforced concrete on top of a concrete water basin. Special attention is paid to maintenance problems especially those associated with dirt and fouling. The tower design provides easy access to the nozzles, drift eliminators and packing with access doors installed at the top of each tower cell. The nozzles have large orifices, which do not clog easily, and fill material is the open splash-grid type which performance is not affected by fouling.

Bulk air coolers

Recently multi-stage horizontal spray chambers have been designed for surface bulk air coolers instead of conventional vertical fill-packed towers. In these spray chambers the water is sprayed, collected and re-sprayed so as to produce a highly efficient air cooler. The horizontal spray chamber is more versatile in operation/functionality and control flexibility [vary duty during life-of-mine], quicker and easier to build, more maintenance friendly and generally cheaper in both capital and operating costs. The nozzles use large orifices, which are not susceptible to fouling, and there is no fill that can be fouled and lead to a fall-off in performance.

With the completion of seven installations in South Africa and South America in the last 7 years [all of which are operating excellently] and a further four in design stage, this approach has become the norm for most future surface bulk air cooling installations.

System layout

With the use of refrigeration machines that use non-toxic refrigerants there is no need to locate refrigeration plants distant from the air cooler and downcast shaft. In recent installations the bulk air cooler [horizontal spray chamber] and refrigeration plant are installed next to each other with a common dividing wall. This arrangement minimises on piping and pumping costs associated with distributing chilled water between the plant room and the bulk air cooler.

CONCLUSION

The principles of design of state-of-art ventilation and cooling systems apply to all of the system design and operating stages. It starts as early as setting primary design criteria and continues to the active operating of supply systems throughout the life-of-mine.

System performance is therefore maximised by determining optimum design airflow quantities and wet-bulb temperatures, using innovative system components, cleverly integrating already efficient components, and finally by cyclical and on-demand operation.

The necessary knowledge and technology exist in most cases to drastically improve ventilation and cooling system efficiency, and it is a matter of applying sound principles and being energy conscious during the design phase. Energy efficiency is paramount and international pressure to preserve global energy resources dictates this approach in all future mine designs.