2-2016

# Current Developments and Challenges of Underground Mine Ventilation and Cooling Methods

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## Recommended Citation

Amin Kamyar, Saiied Mostafa Aminossadati, Christopher Leonardi, and Agus Sasmito, Current Developments and Challenges of Underground Mine Ventilation and Cooling Methods, in Naj Aziz and Bob Kininmonth (eds.), Proceedings of the 2016 Coal Operators' Conference, Mining Engineering, University of Wollongong, 18-20 February 2019
https://ro.uow.edu.au/coal/615

# CURRENT DEVELOPMENTS AND CHALLENGES OF UNDERGROUND MINE VENTILATION AND COOLING METHODS

**Amin Kamyar[1], Saiied Mostafa Aminossadati[1], Christopher Leonardi[1] and Agus Sasmito[2]**

*ABSTRACT*: The mining industry has experienced a dramatic change over the past 20 years in terms of methods and equipment as well as human resource policies. These changes have had impacts on the design of mine ventilation systems. Although feasible developments have been implemented to some extent, in some other areas ventilation planning still requires further improvements to provide a healthy work environment at a reasonable cost. The boom in energy costs has also encouraged mine ventilation designers to seek for efficient use of energy and optimization strategies. The electricity consumption by mine refrigeration plants should be reduced possibly without any adverse effects on the safety of workers. This study presents an overview of the latest techniques used by the experts to address these issues. A revision of the novel ventilation strategies and mine refrigeration methods, and their ultimate effect on efficiency and mining costs would be identified. Finally, likely future developments in the area of mine cooling are outlined.

## INTRODUCTION

Australian mines are directed toward deeper underground operations as exploration tools discover orebodies located at great depths. Deeper working environments imply the need for a feasible means of combating thermal pollution. Workers subjected to heat stress experience serious hazards in terms of health, safety, productivity and morale (Brake 2002). In general, there are two common strategies for underground cooling; one is the use of mine ventilation and the cooling effect of the airflow; and secondly use of refrigeration to provide working areas with low-temperature environments. Despite the recent developments in mine air-conditioning, many Australian miners still suffer from thermal discomfort while on duty (Brake 2001*a*). Thus, higher cooling capacities at deeper levels becomes the major concern of mining companies which imposes higher initial and operational costs. The rise in energy costs on the other side, has made the companies seek for energy management strategies that rectify the inefficiencies of current refrigeration systems or reduce excessive power consumptions. In order to achieve an energy efficient mine cooling system, determination of some factors are essential. These factors include optimum airflow and wet bulb temperature values, applying novel plant components, appropriate integration of components and on-demand plant operation (Marx *et al.,* 2006). Obviously, the implementation of energy efficient projects must not counterbalance the comfortable working conditions for workers. To attain this goal, an exhaustive knowledge of the available technologies and their functionality for different conditions is vital. This paper aims to give an overview of the latest mine cooling strategies being practiced in different mines. The characteristics of these technologies are presented in the form of artificial (refrigeration) methods. In addition, the available optimisation and energy efficiency technologies are outlined along with reported effects from the reviewed case studies. This study will hopefully shed light on the current status of mine ventilation and refrigeration as well as potential energy management techniques for future Australian mining operations.

## MINE COOLING STRATEGIES

With the increase in the temperature of the underground working environment, the conditions approach an allowable upper limit called *heat stress index*. When the conditions surpass this index, operations must be curtailed unless a suitable mine cooling strategy is introduced. There are various heat stress

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indices used worldwide such as dry-bulb temperature and wet bulb temperature of which the latter is quite common since it is appropriate for humid environments as well. For instance in Australian mines, the rule of thumb is that with average temperatures exceeding 28°C wet-bulb (on the hottest days) or the temperature of any working area exceeding 32°C, an underground cooling method must be implemented. Each of the available cooling methods has its own merits and demerits. The satisfactory function of the mine air-conditioning system provides the hot underground mines with the opportunity to exploit deeper reserves and to increase production. Figure 1 shows the hierarchy used by Anglo American operations in terms of different cooling strategies for South African mines. With Australian mines being affected by similar conditions, the trend is to implement the experience obtained for the gold and platinum mines of South Africa. However, the dynamic nature of longwall mining (with frequent moving face) brings about the need for a hierarchy of various strategies for coal mining (Belle and Biffi, 2010).

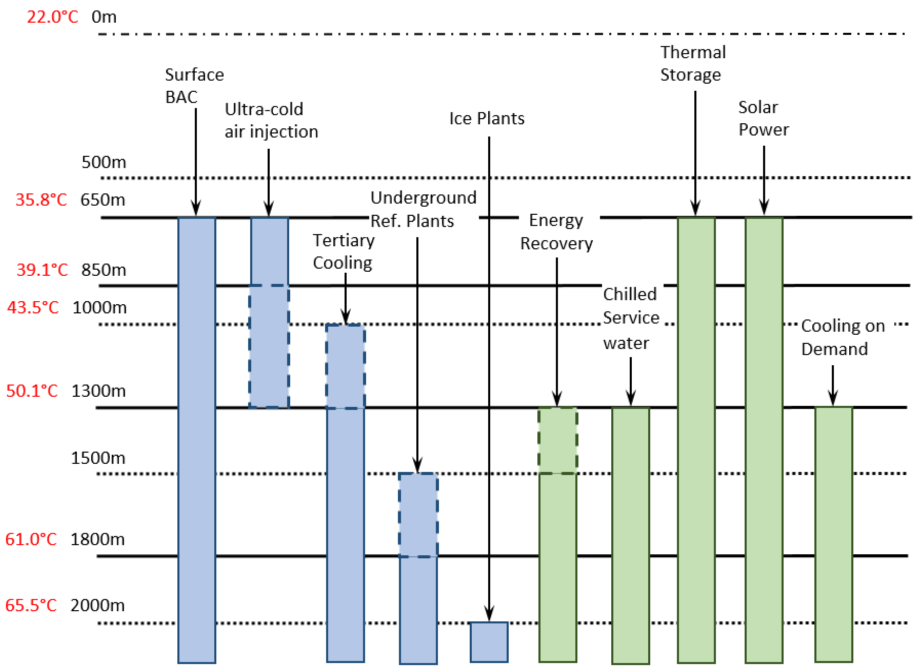


**Figure 1: Hierarchy of implemented cooling strategies by Anglo American operations for South African mines (Belle and Biffi 2010)**

## Artificial cooling strategies

The first use of artificial cooling for underground mines goes back to 1860s when heat control was done by transporting blocks of ice underground in ore cars. However, the earliest use of vapour compression refrigeration was in 1921 to cool an underground mine at a depth of about 2400 m at the Morro Velho mine in Brazil (McPherson 2012). In Australia, a 3 MW plant that used chilled water to cool the deep environments with the aid of high-pressure coil heat exchanger was installed at Mount Isa for the first time in 1960s. However, the first surface refrigeration system for an Australian coal mine was in the Bowen Basin at Central Colliery for a depth of 542m about two decades ago (Belle and Biffi 2010).

## Mine Refrigeration plants

*Surface Bulk Air Cooling*

Currently, surface Bulk Air Cooling (BAC) is the most commonly-used cooling technique in Australian coal mining (Figure 2). The largest surface BAC in Australia operates at Mount Isa with a capacity of 36 MW of refrigeration (Van Baalen and Howes 2009). The vapour compression cycle works via compressing the refrigerant vapour to a high pressure (and high temperature) before sending it to the condenser (a heat exchanger) where it reaches a liquid form. Condensation is done with the aid of cold water coming from cooling towers. High pressure liquid then flows into a receiver followed by an expansion valve. Upon passing through the valve, the liquid refrigerant experiences an abrupt drop in pressure (along with a dramatic drop in temperature) and sudden expansion (flash off) resulting in the evaporation of the liquid. The low-pressure liquid then flows to the surge drum which separates the liquid and gas phases to ensure only vapour is sent to the compressor. The liquid refrigerant passes through the evaporator (another heat exchanger) where it absorbs the heat from air or water and boils. The vaporized refrigerant then enters the compressor and the refrigeration cycle restarts (McPherson 2012). Efficiency of each of these components affect the Coefficient of Performance (COP) of the refrigeration cycle.

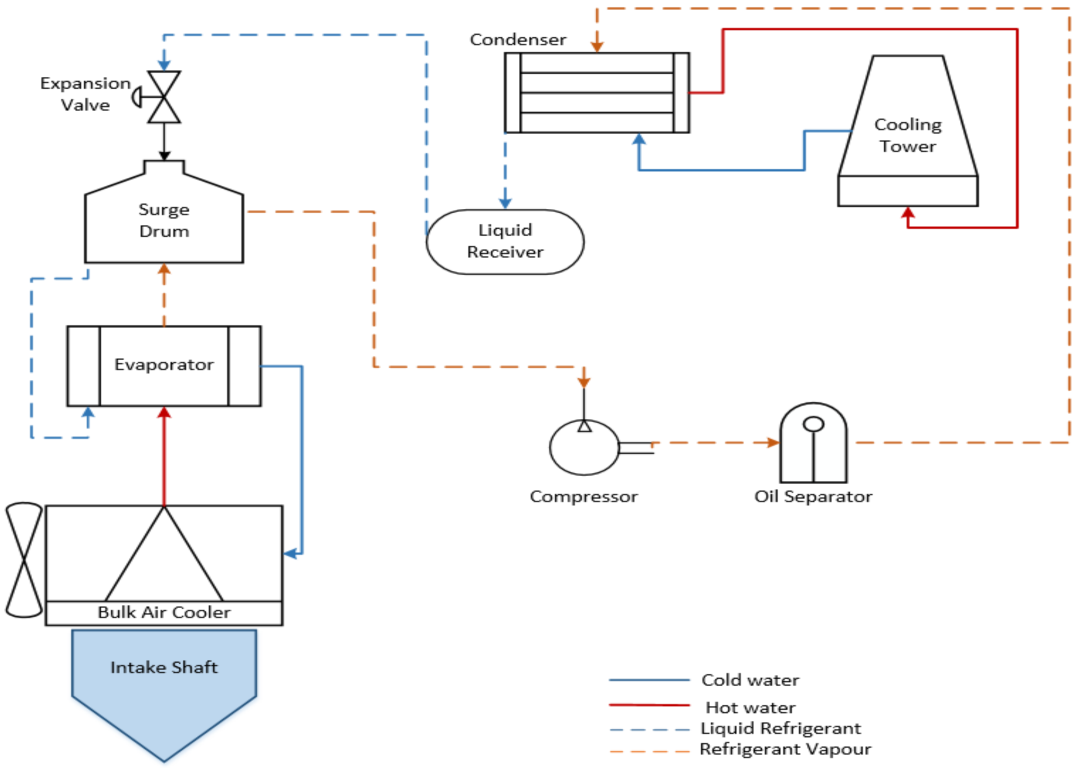


**Figure 2: Schematic of a typical surface Bulk Air Cooling (BAC) refrigeration plant**

Brake (2001*b*) indicated the key engineering considerations in the design of mine refrigeration plants. The author outlined the major components as screw compressors, refrigerant and plate heat exchangers as evaporator/condenser as well as cooling towers require specific design criteria. Recently, Hooman *et al.,* (2015) presented an inclusive step-by-step guide for proper selection and design of mine BAC heat exchangers in terms of parameters such as size, location, inlet conditions, water loading, environmental conditions and surrounding activities. Lack of a unique design code for mine cooling plants, has prevented most plants from fully exploiting the refrigeration capacity (Brake 2001*a*). The major challenge encountered when using this technique is to ensure the arrival of acceptable cooled air at the coal face considering the long distance from the plant.

*Underground cooling techniques*

Despite all the advantages of surface BAC, implementing an underground solution for thermal pollution especially for ultra-deep mines becomes essential. Underground refrigeration is usually maintained by: chilled water from surface, secondary cooling of air, recirculation in ventilation districts or tertiary (in-stope) cooling. For longwall and development, the trend is to locate a coil heat exchanger (BAC) in a mined loop. Chilled water is then pumped through the insulated steel pipes (installed boreholes) to the underground coil BAC. A great proportion of the intake air is directed to pass through the BAC chamber with the aid of air locks or auxiliary fans (Belle and Biffi 2010). Figure 3 demonstrates the schematic of the overall design of such a system studied by O'Connor *et al.,* (2013) to evaluate the feasibility for a Bowen Basin mine. On the right hand side, location of the heat exchanger is shown relative to the longwall panel. Comparing the positional efficiency of the various methods (surface BAC without underground cooling; surface BAC with underground cooling and underground cooling only), the authors found that utilising the underground heat exchanger alone is the best option.

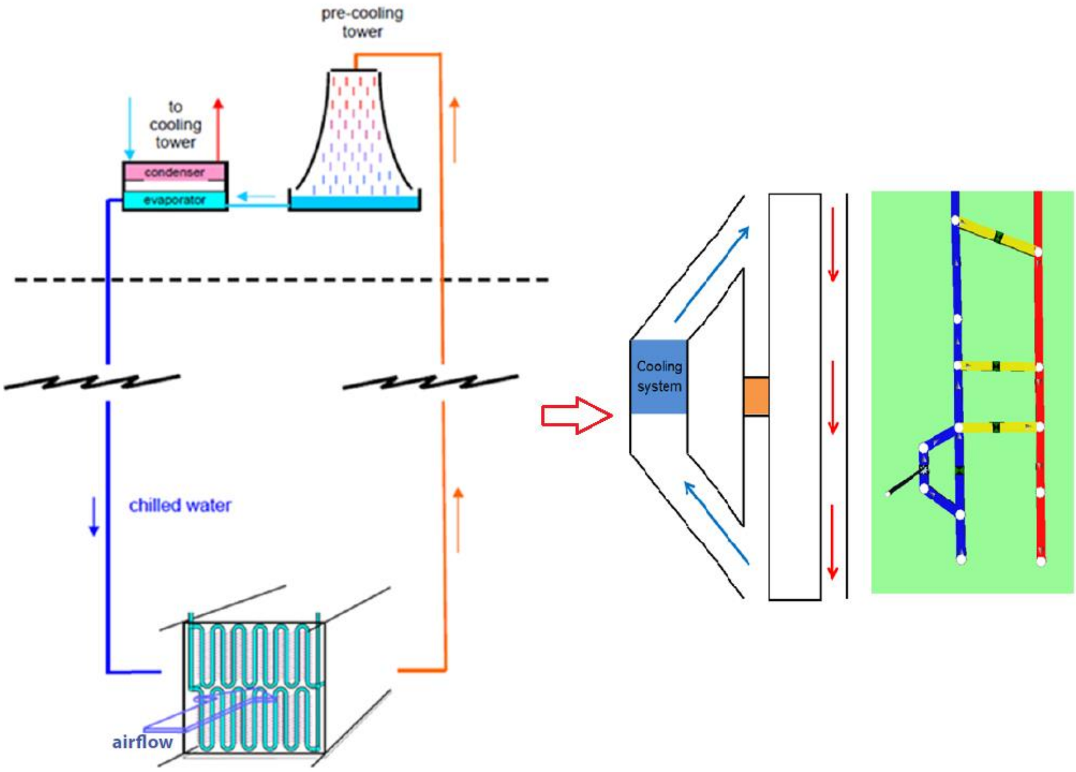


**Figure 3: Schematic of an underground cooling system and location of the BAC for a Bowen Basin mine (O'Connor et al., 2013)**

With the increase in the mining depth and the pumping distance, the operational cost of an underground BAC also rises. Locating the refrigeration plant underground, is another method that shortens the distance in which chilled water (air) travels. An example of such systems is presented in Figure 4. This technique was studied by Ramsden *et al.,* (2007) and compared with surface cooling systems. The major limitation regarding the use of this type is the insufficient means of heat rejection which is the return air only. While surface plants reject the heat to the general ambient air, the limited hot air flow in the intake airways has adverse effects on the efficiency of underground plants. This is along with higher comparative costs due to the needs for high-pressure compressors, extra excavation and installation (van den Berg *et al.,* 2013). For coal mines, another challenge stems from the frequent movement of equipment with longwall as compared with metal mining.

Thus, in some cases the underground refrigeration system consists of two components: the main refrigeration plant chamber/chillers as well as the movable component which comprises air coolers (coil heat exchangers) with a water distribution network. Some other mines use a "hybrid" system which is a mixture of surface BAC and underground refrigeration with BAC located in critical locations. For instance, this system was planned for a block cave operation copper mine in Arizona, USA including surface BAC with a capacity of 105.2 MW and underground air coolers providing 38.5 MW (Bluhm et al., 2014).

*Mobile localized (spot) cooling*

When the evaporator of the refrigeration unit is in direct contact with the airflow at the place where cooling is required (ie face cooling), the absorbed heat in the condenser is also dumped directly to the return air. Benefits of this system is the immediate cooling at the spot and no loss in efficiency due to water reticulation. Spot coolers work on the same basis as domestic air-conditioning units except that the heat is rejected to the outside atmosphere (McPherson, 2012). District cooling has been implemented in South Africa since 1950s with capacities ranging from 100 kW to 500 kW. The use of mobile spot coolers is a prevailing strategy for cooling German coal mine longwall faces as well. This technique is likely to be used in Australian mines with the increase is mining depths. However, the challenge is the necessity for an approval for the operation of such coolers in Australian mines (Belle and Biffi, 2010).

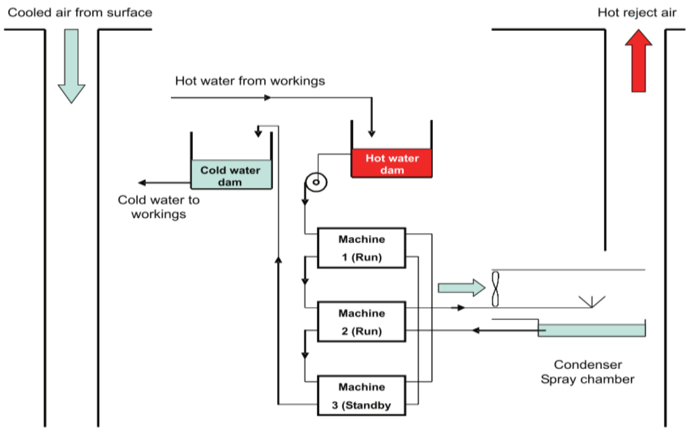


**Figure 4: Schematic of underground refrigeration plant (Ramsden et al., 2007)**

Due to the large energy consumption of conventional vapour-compression cooling systems, some alternatives are introduced for spot cooling in mines. One of these techniques is the use of vortex tubes. This device, invented by Ranque (1933), works based on the fact that if the vortex motion of a fluid is confined in a cylindrical tube a significant temperature separation occurs causing one end of the tube to cool down and the other to warm up. This phenomenon takes place without the help of any moving parts. Despite the relatively low refrigeration capacity of vortex tubes, they can be a potential candidate for underground district cooling for many reasons such as light weight, usable when electricity is not available, low initial cost, instantaneous operation and no need for expert operator (Ameen, 2006). Figure 5 delineates the overall system and detailed structure of a vortex tube. Upon injection of the high pressure fluid, a major part of the fluid rotates and moves forward along the periphery of the tube. However due to the nature of the fluid dynamics, the inner part of the flow returns toward the cold exit. As a result of a pressure gradient created by the forced vortex, a cold core is formed near the injection leading to temperature drops (Xue et al., 2013).

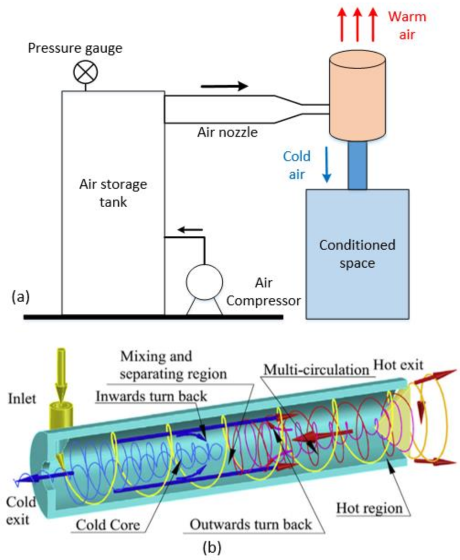


**Figure 5: (a) A vortex tube refrigeration system (Ameen, 2006) (b) flow structure inside a vortex tube (Xue et al., 2013)**

Although the function of a vortex tube seems different from regular cooling systems, it can be analysed as a classic thermodynamic cycle to analyse the temperature, pressure and velocity profiles (Ahlborn and Gordon, 2000). The feasibility of using vortex tube refrigeration for underground cooling was investigated by Jinggang et al. (2009) for the first time. The authors indicated the beneficial application of this technique due to some reasons such as: making use of compressed gas underground, possibility of moving the system with the mine working face, no need for long pipping, major cost saving and overall reduction in greenhouse gas emissions. The work on this type of cooling strategy is still immature and should be extended for future potential mining applications. Another novel proposal to provide district cooling in underground environments is the use of high-pressure water as the driving fluid in an ejector refrigeration system (Butterworth and Sheer, 2007). Figure 6 illustrates the schematic of a water vapour refrigeration unit and its major components. The working principle of an ejector is based on gas (vapour) extraction from a space via discharging a motive fluid (water). The fluid exits as a jet through a nozzle acting as a vacuum pump that draws the gas (vapour) into the diffuser and mixing tube. Transfer of energy between the water jet and the low-energy vapour, leads to the mixing of fluids resulting in condensation of a great part of the vapour (Raynerd, 1987). Upon cooling the water to a certain temperature, if the pressure is adjusted to a value lower than the saturation pressure of that temperature, water will start to boil. Due to the high enthalpy of vaporization of water, a small mass fraction (0.17%) should be evaporated in order to have a reduction of 1°C in temperature. Steam-jet ejectors can provide the low pressures required for this purpose. The ultimate result is the removal of heat from the evaporator section by the motive water jet. Butterworth and Sheer (2005) investigated the potential functionality of such systems for underground cooling using the available mine water. It was concluded that this technology can be implemented for backfill cooling. The backfill usually imposes a heat load on the ventilation itself. Installing a cooling ejector system on the levels above the stopes, a high-pressure water jet will reduce the temperature of the backfill efficiently.

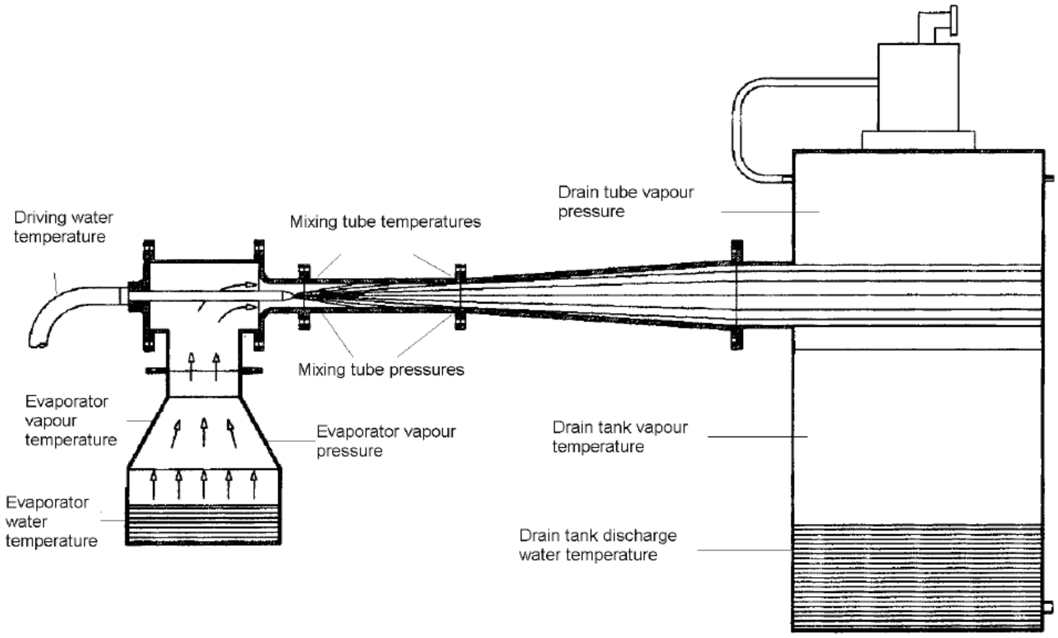


**Figure 6: Schematic of an ejector for water vapour refrigeration (Butterworth and Sheer, 2007)**

*Ice Cooling Systems*

The use of ice from the surface for underground cooling dates back to 1927 but was found to be inefficient and infeasible (Gebler 1980). Later, South African Mponeng mine tested the use of ice to provide cooling at a depth of 4km with rock temperatures reaching 55°C. Compared to chilled water, with a reduction of 70% in the mass flow rate the same cooling capacity can be provided using melting ice. The initial, operating and maintenance costs of ice-producing power plants are high. For the case of South African mines, the advantages of running such systems outweighs the cost-imposed burdens when a pumping head of 2500 m is reached. This can be the case for future Australian ultra-deep mines as well (Belle and Biffi 2010). When water is pumped underground, its temperature goes up as a result of its potential energy being converted to heat. As indicated by Kidd (1995), for the case of Vaal Reefs mine, an increase of about 2.4°C per 1000 m of pipe-run were measured. Whereas for ice slurry, the mixture temperature remains constant due to melting of ice. In another study by Ophir and Koren (1999) the application of ice slurry for underground cooling at the Western Deep Level Gold Mine, South Africa was described. An ice slurry plant comprised of four 3 MW units was used to produce the ice slurry transported to depths of 4000 m with the aid of gravity. Mackay *et al.,* (2010) carried out a comparative modelling to specify the break-even depth at which each refrigeration mode should be applied for Impala Platinum mine, South Africa. They discovered that despite the excessive growing trend of required flow rate of chilled water, the ice flow rate for the same refrigeration capacity is still affordable at lower depths. It was also indicated that in terms of cost analysis, after a depth of 2900 m the results are in favour of ice cooling method. It is noteworthy that ice can also be produced for other purposes than underground cooling, which is the thermal energy storage and load shifting capability. These systems are particularly worth implementing where power tariffs are levied such that substantial savings can be achieved by producing ice at night (off-peak periods) and using it during daytime at peak tariff times. In terms of power cost saving, this technique might not be profitable for Australian mines due to fixed tariffs; however, it could help to install a smaller refrigeration plant by load profiling where there are electricity constraints (van den Berg *et al.,* 2013). For this application, the refrigeration plant consists of two components: primary (base load) machine and thermal storage dam. Chilled water exits the former and then enters the latter which contains tube banks. Glycol passes through these tubes and causes a layer of ice to be formed during low-temperature periods throughout the day. The formed ice then adds to the cooling capacity by melting during hotter periods of operations (Bluhm *et al.,* 2014). Figure 7 shows the schematic of such a system.

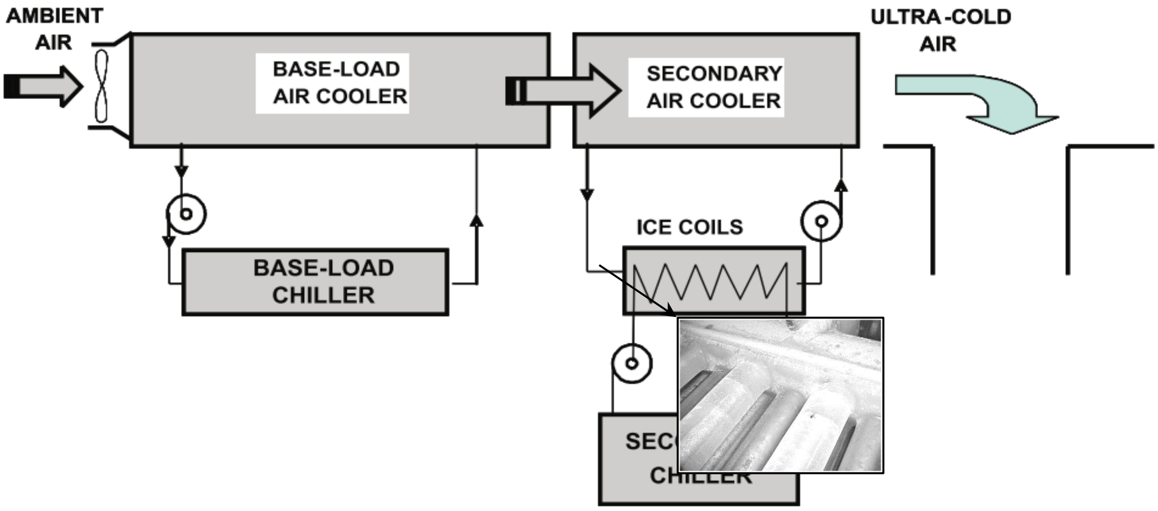


**Figure 7: Schematic of refrigeration plant integrated with ice thermal storage (Ramsden *et al.,* 2007)**

Aside from the mentioned novel methods, seasonal thermal energy storage has found its way to the mining industry, recently. In the summer, heat is stored within the rock-pit to be used later on for heating in the winter, while the "cold" energy is captured and stored in the rock-pit for cooling in the summer. This has been utilized as a "natural heat exchanger" at some areas such as Creighton mine in Canada. Seasonal ice thermal storage is another method which includes the converting the warm service water into ice by spraying it into the incoming sub-zero ventilation air in winter. This technology used in Stobie mine in Canada, then uses the stored ice in summer to produce chilled water. Mining industry should be more aware that renewable energy can be harvested and used for mine cooling which can lead to energy savings, carbon footprint and cost reduction.

## OPTIMIZATION AND ENERGY SAVING METHODS

### Monitoring and Control

With the advent of automation technologies, it is nowadays possible to implement an accurate monitoring and control technique to observe the conditions of air temperature and velocity, contaminants and water flow. Real-time Energy Management System (REMS) is currently drawing more attention as a tool providing an optimized schedule for refrigerating the hot underground areas (Webbeer-Youngman 2005). The purpose is to reduce the energy consumption of mine cooling with the aid of technologies such as Variable Speed Drives (VSD), control valves and other Demand-Side Management (DSM) methods. Pelzer *et al.,* (2010) implemented this strategy for three South African mines to monitor and optimize the inlet chiller temperature. They reported a value of 32 416 MWh reduction in electricity consumption due to the increase in the Coefficient of Performance (COP) of the plant. The application of the same monitoring system was also reported by Vosloo *et al.,* (2012) for a water reticulation system at Kopanang mine, South Africa. The authors claimed that a 2% reduction in overall power consumption corresponding to an annual cost saving of US$ 636 400. In another study by du Plessis *et al.,* (2013*a*) the outcome of implementing various energy saving strategies for the Kusalethu mine in South Africa was reported. The applied strategies included evaporator and condenser flow control using VSD, BAC water flow control using valves and retrofitting of old pre-cooling towers. The implementation of these strategies was found to result in a saving of about 31% in the total plant power consumption while keeping the refrigeration and ventilation requirements met and the COP of the cooling system enhanced overall (See Figure 8). As one of the techniques, the effect of VSDs was investigated by du Plessis *et al.,* (2013b) for 20 South African mine cooling systems. It was concluded that a power savings of about 168 633 and 144 721 MWh/year is achievable by installing VSDs on chiller compressor motors and all pump motors, respectively. Mare *et al.,* (2015) also explored the effect of energy saving strategies by varying the flow according to the demand for two mine case studies. VSDs were installed on the evaporator, condenser and BAC pump motors. For the evaporator, the strategy helped to monitor and control the dam level while for the condenser it provided a fixed temperature difference within the condenser vessel. Reduction of full-load conditions for the BAC and a fixed constant wet bulb temperature (8°C) was also attained. Beside these merits, the major barriers of using VSDs are mainly indicated as technical (non-linear loads), economic (high price) and awareness (personnel scepticism about achievable energy saving) issues. By addressing these issues, implementation of VSDs for Australian mine cooling system might be more common in future.

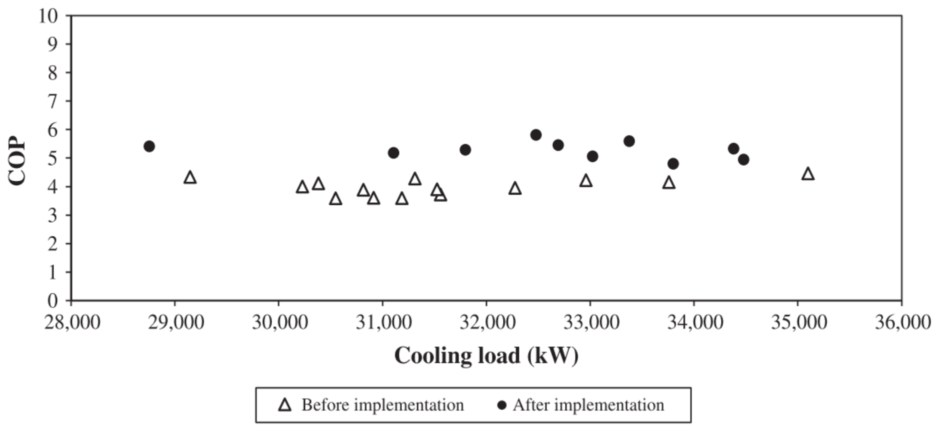


**Figure 8: COP of the cooling system before and after implementing the energy saving strategies (du Plessis et al., 2013a)**

In recent years, another strategy has been instigated in Chinese mines which is based on extracting the cold from the underground water inrush (a phenomenon in which water resources suddenly fill the space of the mine during mining processes) to cool the warm airflow (Gao and Liu 2009). In summer, High-temperature Exchange Machinery System (HEMS) is able to provide cooling to the working environment as well as buildings. The system also helps to provide the extracted heat from water inrush for buildings and showers in winter (Ping *et al.,* 2011). Figure 9 shows the layout of this system comprising of closed-loop water as well as open-loop air circulation systems. Since the refrigeration plant (chilling water) and air cooling station are located at different levels, a pressure transition is also installed to reduce the pressure when reaching lower levels. Qi et al. (2011) reported the operational effects of this system for the Sanhejian coal mine, China for a depth of 1000 m. They indicated that the airflow temperature at a point of the working face decreased from 38°C to 30°C. This method is claimed to bring about environmental benefits and economic sustainability in addition to energy management. A similar thermal energy management system was introduced by Niu (2015) where a heat recovery system was utilised during winter. A two-stage cooling system was proposed that made use of the lower underground cooling requirements in winter, to run the heat pumps in heating conditions by recovering heat from the low temperature mine return air and mine water.

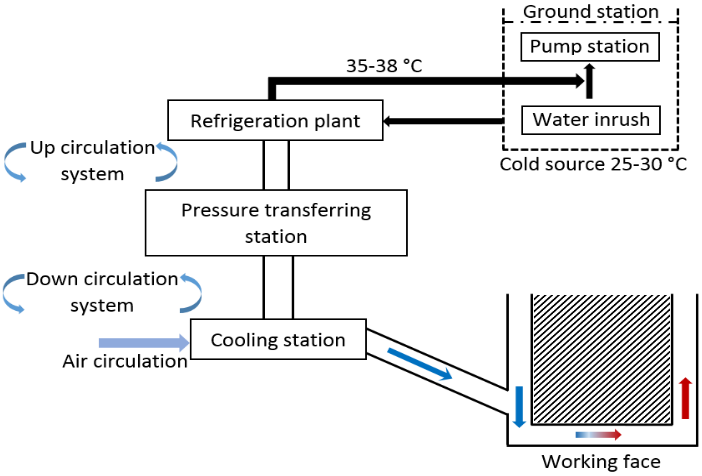


**Figure 9: Schematic of HEMS cooling system (Manchao et al., 2010)**

## CONCLUSIONS

This paper presented an overview of the common trends in mine ventilation and refrigeration as well as more recent energy efficiency and optimization practices in underground cooling. Despite all the recent developments in South African mines, many Australian mines are still lacking a mining code of practice for heat management in mines. If the sources of heat in the underground environment are measured in an accurate way, a suitable cooling strategy can be proposed which is an inevitable fact with the increase in depth of mines in future. Energy efficiency and optimization strategies will address the concerns of management in terms of functionality and cost-effectiveness of these strategies. Introduction of novel monitoring systems, implementing control strategies to obtain cooling-on-demand, thermal energy recovery from available resources and improving the performance of current cooling plants are the main ways to achieve this goal. Previous case studies acknowledge that large financial benefits can be acquired if refrigeration plant of a mine is optimised.

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