Operational advantages of monitoring air cooling units in remote underground areas

M.N. Ras
M – Tech Industrial (Pty) Ltd

M. van Eldik & R. Potgieter
North-West University

ABSTRACT: Typical mines in South Africa have numerous critical systems that need to remain operational for productivity. One such critical system is mobile refrigeration air cooling units. These refrigeration units provide cooling for the active stopes or developmental ends that require cooled air for a safe working environment. This study focuses on the operational advantages of monitoring infield operating conditions of refrigeration units in remote underground areas. This paper will use data from underground installations to show how reliability, performance and availability can be improved using monitoring systems. Data is gathered locally at each refrigeration unit, with the use of custom designed loggers, and analysed using data analysis software. The report generated for each refrigeration unit provides insight into the root cause of system shutdowns/downtime or failures. This allows the mine to minimise future interruptions or failures and do preventative maintenance as and when required, ensuring maximum cooling is delivered.

1 INTRODUCTION

The South African mining industry is continuously looking for ways to improve their critical systems with regards to reliability, energy efficiency and safety. A critical component of underground mining is its ventilation and cooling systems (Cheng et al, 2011). In labour-intensive mining operations, it is impossible to increase production and safety without considering the ventilation and cooling performance of the area. An individual's ability to concentrate diminishes above a certain level of heat stress leading to increased accident rates. Above the effective temperature of 27°C, an individuals' ability to complete complex tasks and perform intensive labour also greatly diminishes, leading to a decline in production (Stewart, 1982). The findings support the use of effective temperature to characterize the effect of heat stress in relation to human performance and the likelihood of disabling injuries. However, it was also found that the curves coincide when cooling power is used in the place of effective temperature. The development and maintenance of a sufficiently cooled environment are thus of critical importance to ensure that the performance of individuals remains high whilst the occurrence of accidents remain as low as possible. Figure 1, illustrates the decline in human performance with an increase in the effective temperature at different flow velocities.

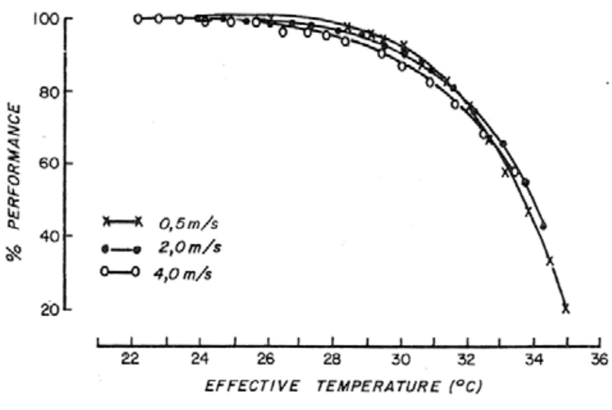

Figure 1: Performance vs. Effective Temperature (Stewart, 1989)

With low margins of profitability, some mines are under pressure to increase the production and efficiency of the mining operations in all departments including ventilation and cooling (SA mines, 2017). This remains a challenge as mining operations expand vertically deeper and horizontally further from the shaft inlet. The temperatures of air and chilled water supplied from surface increases as travel distances increase from the shaft inlet. The resulting heat gains can be countered by increasing volume flow rates; however, this has a direct impact on the cost of cooling and ventilation. The increased cooling cost has a negative impact on the profitability raising concerns about expanding or continuing mining operations in these remote areas. The higher costs associated with the installation of infrastructure to enable mining in remote areas also makes it less attractive to pursue these possibilities.

To counter the cost increase of mining remote underground areas, spot cooling using mobile refrigeration cooling units that can move with the development becomes attractive (Potgieter, 2017). However, due to the small profit margins, efficiency and productivity is key when mining within remote underground areas. It is therefore crucial that these mobile cooling units are not only reliable but efficient as cooling has a direct effect on production. By monitoring the operational conditions of mobile refrigeration units, the performance and efficiency can be increased and the equipment maintained more effectively.

2 SPOT COOLING

2.1 *Brief overview*

Localized cooling, also known as spot cooling, focuses on the cooling of specific underground working areas using localized or mobile cooling units. These cooling units work in conjunction with traditional infrastructures such as fridge plants or ice plants, bulk air coolers (BACs) and chilled water reticulation systems to cool specific active working areas within the mine.

The two main types of localized cooling units that will be discussed in this section are chilled water cooling cars (CCs) and mobile refrigeration air cooling units (ACUs).

Cooling cars are air-to-water heat exchangers, combined with fans, mounted in a chassis on rolling stock which enables the units to be moved and installed in different areas of the mine (Potgieter, 2017). The performance of a cooling car is highly dependent on the chilled water supply temperature and flow rate.

The mobile refrigeration air cooling unit (ACU) is a mobile refrigeration unit which consists of a refrigeration gas cycle in a chassis mounted on rolling stock. The feasibility and energy efficiency of these cooling units was first investigated by Prof. van Eldik in 2007 (van Eldik, 2007) and further energy efficiency studies were done by Dr Rankin (Rankin, 2011) and Mr Potgieter (Potgieter, 2017). The units have a nominal cooling capacity of 100 kW or 250kW respectively and are selected depending on the requirement of the particular mine. An ACU can function with or without chilled water, increasing its applicability and performance in remote underground areas. When supplied with chilled water the units were found to be a more energy efficient alternative than using CCs as the unit could remove more heat from an area while utilizing a smaller amount of water. By decreasing the amount of water required during cooling operations, the water being pumped to the surface is reduced. This subsequently reduces the electrical consumption and pumping costs related to cooling (Potgieter, 2017).

2.2 *Performance factors and their challenges*

The cooling capacity of CCs and ACUs are dependent on, although the ACU is less sensitive to, four inputs namely the air mass flow rate, the water mass flow rate, air temperature (dry bulb and wet bulb) and the water supply temperature. The challenge is, therefore, keeping these input parameters within the required limits for maximum cooling and efficiency. The monitoring system investigated within this study aims to monitor, identify, manage and thereby reduce the major challenges with regards to performance and efficiency.

2.2.1 *Supplying chilled water to the localized cooling unit*

One of the challenges of underground cooling operation is the supply of the correct amount of chilled water to the localized cooling units situated at remote mining areas. The water travels down long pipe networks; heat is picked up increasing the inlet water temperature to the localised cooling unit. A higher inlet water temperature means an increased water flow rate required to maintain a certain cooling duty. This also has a negative effect on the unit's efficiency as a higher water flow rate results in higher pumping costs. The water flow rate can however be too high further increasing pumping costs with no benefit to cooling performance. The ACU is also affected by a higher inlet water temperature but the effect is limited because of the refrigeration cycle, which enables the condenser water to be heated to a temperature higher than the supply air temperature. The approach temperature between inlet air temperature of the water and the air outlet temperature seen in a CC, which is dependent on the air and water flow rates, are replaced in the ACU by an operating envelope (minimum inlet air temperature and maximum water outlet temperature) due to the refrigeration cycle. By monitoring the inlet water temperature, the water flow rate for CCs and ACUs can be manually adjusted or mechanically regulated to give the optimal flow rate or desired outlet water temperature. Manually adjusting hand valves are limited in their effectiveness as infrastructure surrounding the spot cooling unit affects pressure and subsequently water flow rate. The water flow rate can, however, be regulated using a pressure regulating valve ensuring the pressure or flow rate remains practically constant. By supplying only the required flow rate maximum performance and efficiency can be obtained if the supplied water flow rate and pressure are sufficient.

2.2.2 *Fouling of the air heat exchanger*

The localized cooling units are located close to active mining areas, which typically result in higher amounts of dust and other contaminants. Dust or other particles in the air causes fouling on the heat exchanger's finned surface. This causes a decrease in heat transfer affecting the performance of both the CCs and the ACUs. The decreased heat transfer lowers the amount of cooling delivered or increases the amount of water required to obtain the target amount of cooling. By monitoring the water flow rate, temperatures and overall performance of the localised cooling unit, reduction trends can be studied to ensure maintenance is done as and when required.

2.2.3 *Scaling inside a heat exchanger*

Due to the hardness of the cooling water supplied to localized cooling units, scaling of the unit's heat exchanger is a challenge faced by both CCs and ACUs (even more so in ACUs due to the higher water temperatures reached). Various chemical elements such as carbonates cause scaling on the heat exchanger surface, resulting in a decrease in heat transfer. By monitoring the performance of the system, preventative maintenance can be planned to reduce performance limitations or downtime by scheduled descaling of the heat exchangers. An added benefit of the monitoring system is that a performance baseline is established to determine if the descaling operation was successful or if subsequent descaling operations are required to fully counter the effect of scaling in the condenser units.

3 LITERATURE ON UNDERGROUND MONITORING SYSTEMS

To illustrate the advantages of an underground monitoring system, two completed case studies from literature will be discussed in this section.

3.1 *Development of a Real-Time Airflow Monitoring and Control System*

The study by Gillies et al. (2004) focused on the development of a computerized monitoring and simulation system to improve the effectiveness of air ventilation distribution throughout a mine's ventilation network. The study found that by monitoring certain key parameters such as air pressure and flow rate, accurate models could be created using "Ventsim" simulation software. The models were then used to simulate ventilation conditions in various branches of the mine. By using the simulation software along with the monitoring equipment the mine was able to increase the effectiveness of their ventilation network by monitoring changes is certain branches of their ventilation network. The study found that it was able to detect changes occurring within the mine ventilation system accurately and identify constraints that will limit the performance of the system. The monitoring system combined with software ensured that the ventilation system was able to provide the best possible ventilation on all levels considering the demand. Consequently, the risk of heat stress and fume inhalation was minimized, adding the potential for increased production and mine profitability.

3.2 *Distributed temperature measurements using optical fibre technology in an underground mine environment*

Aminossadati et al. (2009) examined the applicability of a real-time temperature measuring and monitoring system, using distributed temperature sensing by means of an optical fibre network in an underground mining environment. Through this technology, the temperature distribution of the entire underground mine could be measured with an accuracy of 1°C with a distance resolution of 1m. The study found that the use of continuous monitoring of the environment increased the safety within the mine as conditions and changes within the conditions were more closely and accurately monitored. The mine was able to locate "hot spots" in real time and take preventative action to ensure the safety of personnel. The monitored data also provided valuable insight and benefits required by underground ventilation designers and operators.

4 ADVANTAGES OF SYSTEM MONITORING

An automatic measurement system has multiple benefits when compared to physical measurements taken by a person. Measurements can be calibrated against verified hand-held instruments to ensure the measurements taken are accurate and correct. The measurement system can be a real-time monitoring system communicating with a server on the surface for real-time monitoring, or it can be a localised standalone monitoring system when the mine infrastructure does not allow real-time monitoring. The cost difference between a real-time monitoring system and a localised standalone recording system can be substantial; however, most of the advantages of system monitoring remain even if the system is not monitored in real time. The advantages of system monitoring include:

- Continuous system and performance tracking.
- Continues measurements can detect underlying adverse events that affect the system such as power dips or spikes affecting the performance or service life of a system.
- Recorded data can be used after a system failure to assist in the root cause analysis of the failure.
- Monitoring systems can be used to conduct trend studies. Trend studies track changes and their effect during a 24 hour period or even an annual service cycle such as changes in air or water temperatures due to night and day or winter and summer. It can be used to study the effect of shutting down a cooling system for a few days, and then how long it takes to cool the area after heat has built up within the environment.
- Recorded data serves as an established performance baseline that can be used along with trend studies to determine when performance is decreasing. The root cause of the rate of decrease can be studied for maintenance or service planning schedules.
- Recorded measurements can be used to increase the accuracy of models predicting performance within future projects and developments.
- The recorded data from a measurement system can be reported on quickly and accurately using software that is either specifically developed for the data or existing reporting tools.

5 KEY PARAMETERS

The ACU is dependent on key factors that are required to be within a certain range for optimal performance and efficiency. It is important to understand what these factors are, and how they affect the cooling performance of the ACU. By studying these factors the system performance can be maintained at expected levels while ensuring the system is running efficiently. The following key performance factors were identified for the mobile refrigeration air cooling units:

- Inlet water temperature – The inlet temperature determines how much heat can be stored in each litre of water. The inlet water temperature can range between 5°C and 40°C; with a lower water temperature resulting in increased systems efficiency.
- Water flow rate – The water flow rate is linked to the inlet water temperature as the outlet water may only be heated to a temperature of 45°C, with most mines aiming for a more efficient outlet temperature of 40°C. Heating the water to this range gives a balance between efficiency (lower flow rate) and limiting the discharge water temperature to below conditions that can be harmful to personnel that might come into contact with the heated water.
- Electrical supply – The ACU system operates based on a vapour compression cycle similar to what is found in a surface fridge plant. The compressor and fan used for the ACU require 525V ± 10% and a current supply of between 45A and 160A, depending on the ACU model and electrical supply infrastructure.

6 DATA MONITORING

6.1 *Data monitoring system*

The monitoring system used in the study is a custom-designed data logger. The data logger has the capabilities to send real-time data, however, due to the remote location’s limited communications network, the system is set up to function only as a data recorder. Currently, data is recorded for a full month where-after it is collected and studied to make the necessary recommendations for improved efficiency or performance during the following months.

The monitoring system currently measures up to twelve key parameters simultaneously. The monitoring system measures/samples the identified key performance parameters every 15 seconds during the monthly monitoring period. The 15-second measurements are then summarised as a maximum value, minimum value and average value and logged/stored at 5-minute intervals. By summarising the data every 5-minutes the amount of data remains manageable, while the minimum and maximum logged/sampled values ensure major events are captured by the monitoring system.

The key performance factors currently monitored are:

- Inlet water temperature,
- Outlet water temperature,
- Inlet air temperature (dry bulb),
- Outlet air temperature (dry bulb),
- Water flow rate,
- Electrical supply voltage (phase-to-phase),
- Electrical supply current (two phases),
- The internal temperature of the logger, and
- Internal humidity of the logger.

By installing a measuring system and recording these key performance factors the advantages of doing detailed system monitoring can be shown. These key performance factors and measurement equipment can also be expanded to measure for instance methane levels or refrigeration gas pressures and temperatures should the need arise.

6.2 *Data Analysis*

The recorded data is downloaded to a web-based server in a CSV format with each of the key performance factors in a column, while each row indicates the next recorded value of a 5-minute interval for each key performance factor. The data table is then analysed in more detail by the in-house software developed specifically for this. The software analysis program is used to:

- Divide the data into daily segments to allow trend studies and manageable amounts of data.
- Highlight any key performance factor that is either approaching or outside the pre-defined range.
- Indicate any major events such as insufficient water flow or dips and spikes in the electrical supply
- Perform the required calculations on the data to determine system performance and efficiency.
- Highlights any period that the performance or efficiency is increasing, declining or outside of the specified range.
- Assign a system status of "running", "limits" or "off" depending on the monitored and calculated values. ("Limits" indicate that the ACU is working, but outside of the desired range on one or more of the influencing factors)
- Draw graphs of the monitored and calculated values for quick and easy analysis.

6.3 *Summarizing data analysis*

Once the data is analysed for each individual day of the month the daily graphs and summarised data are worked into a monthly report. The monthly report provides a quick summary of the system performance and efficiency while giving details on each event that influenced the performance of the ACU. By automating the data analysis and reporting the performance and efficiency of each unit can be studied quickly and effectively.

7 EXAMPLES OF REALISED MONITORING ADVANTAGES

These monitoring systems as explained above have been installed into ACUs in various gold mines since 2016. The implementation of a monitoring system into a relatively harsh environment proved challenging, however by February 2017 accurately recorded reliable data could be obtained. Since then the monitoring systems provide vital information that gives insight into the performance of each ACU unit. The monitoring systems have proven vital to better understand what is happening underground as will be explained in the following cases.

7.1 *Maintenance advantages*

7.1.1 *Blockage in the water supply*

Data analysis of a monitored ACU found that the performance of the ACU is limited to a maximum or target cooling of 230kW due to water flow rate limitations from the supply. However, after the first month's data was analysed it was noted that the ACU's performance was steadily declining from 230kW cooling throughout the monitored period of one month. It was showing a decline of about 30kW after the first 2 weeks, where after performance declined rapidly. A detailed investigation of the data showed that the performance was declining due to a decline in water flow rate from 10 litres per second to 4 litres per second over a period of 33 days. It was further noted that the decline in flow rate was causing a rise in water discharge temperatures ruling out possible scaling inside the condenser heat exchanger.

It was decided to send a team to specifically inspect the water supply for a possible low pressure indicating insufficient supply or high pressure indicating a blockage in the supply pipe. The team visited the site on the 12th of November 2017 and found that the system is showing high pressure and started searching for a supply pipe blockage. Debris was found on the inlet side of the water pressure dissipater of the specific section, causing the lowered flow rate. The debris was removed and the ACU's performance was restored to target cooling. Figure 2 below shows recorded performance on each day and the increase in performance after the debris was cleared. The service day is marked in orange.

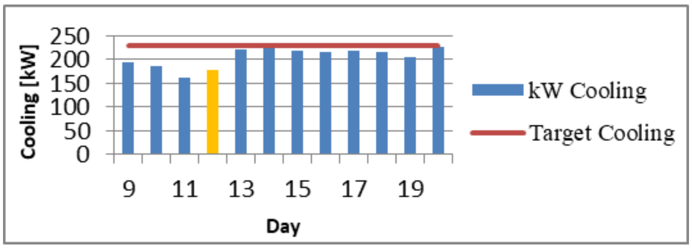

Figure 2. Blockage of water supply.

After the blockage was confirmed the monitored data was analysed to determine the rate at which the dissipater was blocking up. A maintenance schedule was suggested and adopted by the mine to ensure the debris is cleared before performance is affected. The monitored data in the months that followed showed that the maintenance was successfully keeping the ACUs performance at 230kW cooling.

7.1.2 *Scaling inside the condenser*

Data analysis of an ACU found that the cooling performance was steadily declining from 250kW cooling at a rate of 10kW per month for a 4 month monitoring period. A detailed investigation of the monitored data found that the flow rate remained unchanged, but the outlet water temperature was decreasing as the cooling performance reduced. A water sample was taken on site to investigate the probability of scaling and the analysis showed a high probability of scaling due to its composition and the heating effect of the ACU on the water. The decrease in outlet water temperature was attributed to a reduced heat transfer rate indicating fouling or scaling inside the condenser heat exchanger.

A team was sent to descale the unit on the 8th of October 2017. After descaling the condenser the cooling performance increased from 210kW to 235kW. Based on the data recorded the ACU was capable of delivering 250kW cooling under the provided inlet conditions. The team was sent down again on the 11th of October 2017 to repeat the descaling procedure. After the descaling procedure was executed it was confirmed that the cooling performance was restored to 250kW. Figure 3 shows the cooling performance for each day and the increase in performance on the service days marked in orange.

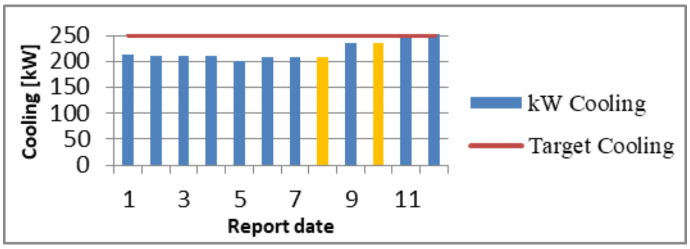

Figure 3. Scaling inside the condenser heat exchanger.

Due to variances in supply and surrounding infrastructure affecting the performance of the ACU the declining performance trend could not be directly identified. However, by studying the performance of consecutive months the declining performance trend and the root cause could be identified. For the specific mine, the rate of performance decline was studied and it was noted that the descaling procedure needs to be completed twice every 4 months to ensure the ACUs performance remains within acceptable limits.

7.1.3 *Blockage of the air evaporator*

A monitoring system was installed on an ACU that has been operational for a number of years. Data was analysed and it was found that the ACU was underperforming compared to other units in the field with similar environmental conditions. A detailed study of the data found that the outlet air temperature was substantially lower than compared systems. The reduced outlet temperature is an indication of a lower air flow rate over the evaporator.

This could be either due to a blocked heat exchanger or a fan that was not performing as expected. An underground inspection found that the heat exchanger was severely blocked and that this resulted in a lowered heat exchange rate limiting the performance of the ACU. After the evaporator was cleaned the ACUs performance increased to 250kW cooling. Data is currently being analysed to determine the maintenance interval for the specific area.

7.2 *Efficiency management*

7.2.1 *Supply valve failure*

Data analysis of an ACU found that the cooling performance was at the target level of 250kW; however, the water flow rate through the ACU was 5.8 litres per second even though only 3 litres per second was required. The ACU's water supply was controlled with a hand valve that was pre-set to regulate water flow rate.

During an underground site inspection attempts were made to reduce the flow rate through the ACU, however, it was found that the valve has failed in the fully open position. Attempts were made to repair the valve, but ultimately it was decided that the valve should be replaced. A further investigation found that the surrounding areas water pressure and the flow rate was also affected by the valve that failed in the fully open position; however, the source of the pressure and flow rate reduction could not be identified. The valve was replaced whereafter the control valve was again set to allow the required flow rate.

The following month's data was analysed and it was found that the water pressure and subsequently the water flow rate varies substantially at the ACUs installed location. A proposal was supplied to the mine to install a pressure or flow regulating valve to ensure water flow rates can be maintained within the required range.

Even though it was found that the installed hand valve could only control the water flow rate to a degree, the water consumption was reduced by 6 257 cubic litres per month by repairing the hand valve. A further reduction of 1 500 cubic litres per month can be obtained with the installation of a pressure or flow control valve.

8 CONCLUSION

There are numerous advantages that can be obtained with continues monitoring of localised spot cooling units. Most of the advantages are retained even if the system is not monitored in real time.

Continuous monitoring systems have proven to be an effective tool for maintaining target performance. The monitoring system successfully identified factors that reduced the cooling performance of the spot cooling units. A strategy could then be developed to reduce or eliminate the effect that these factors have on the performance of the localised spot cooling unit.

The data gathered could be effectively used for trend studies. The trend studies provided the inputs required to create preventative maintenance schedules minimising or eliminating performance limiting factors found in the specific area of the mine.

The continuous monitoring system assisted in identifying specific areas to be investigated during fault finding. By identifying the specific areas, investigation time could be greatly reduced, resulting in increased availability of the localised spot cooling units. The monitoring system further assisted investigations with evidence ruling out possibilities or supporting investigation results.

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