Maximising spot cooling potential when utilising varying mine service-water as heat sink

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ABSTRACT: In recent times the health and safety of the mining workforce has been getting more focused attention. Due to the hazardous and volatile underground environment, a better understanding was required of the effects of environmental factors on health and productivity. The hazards are further compounded by the expanding underground network and mines operating deeper every year. The increasing complexity of underground works and rise in ambient temperatures, compounded by increased VRTs at depth, create unique environmental and ventilation challenges. Effective and reliable ventilation and air cooling are essential in providing a safe, productive workplace underground.

To keep operations economically sustainable, there is an increased focus on spot cooling methods in production areas, thus eliminating unnecessary air cooling of non-operational areas.

Traditional spot cooling is achieved through an air-to-water heat exchanger (also known as a cooling car (ACC)) using chilled water as heat sink in the area to be cooled. The cooling potential is however a function of both the water flow rate and supply temperature. Therefore, the water temperature needs to be much lower than that of the air to achieve any cooling. For vast underground mining operations this can only be achieved via central cooling infrastructure consisting of either surface or underground fridge plants and a chilled water recirculation system.

Another spot cooling method implemented, makes use of a mobile vapour compression refrigeration unit, known as the Air-Cooling Unit (ACU), where water is also utilised as a heat sink. An attractive attribute of the ACU is that it can deliver cooling over a large heat sink range, thus eliminating or reducing the central cooling infrastructure requirements. The ACU can therefore cool air to temperatures lower than that of the incoming cooling water, which is not achievable with a conventional cooling car.

A further advantage is that an ACU can operate at a high energy efficiency level, therefore reducing operational costs. To ensure asset health, favourable operating conditions are required that include adequate supply water flows. However, a mining environment comprises multiple water users at any single time, and it is therefore typically not possible to ensure continuous sufficient water flow availability twenty-four seven. This results in lower ACU operational efficiency, and therefore higher operational costs.

This paper demonstrates the importance, and therefore, operational advantage when an ACU is used where mine service-water is utilised as a heat sink. Furthermore, operational constraints where service-water is available in varying quantities, which results in ineffective air-cooling operations, both in terms of kilowatt hour cooling provided as well as electrical costs per kilowatt hour of cooling provided are addressed through improved compressor capacity control.

1 BACKGROUND

The mining industry makes use of underground air cooling and ventilation to provide a safe working environment for their workforce. It is not uncommon for underground air temperatures to exceed 35ºC dry bulb with high relative humidity percentages. These conditions are hazardous for humans to work in, and potentially fatal without sufficient air conditioning. With an expanding underground network, working in remote areas, it is sometimes very difficult to provide acceptable conditions without spot cooling, due to the excessive costs of a centralised cooling system with its vast piping network, both in terms of capex and operational expenditures.

Spot cooling is a well-known concept where localised cooling is done only in a specific area, allowing personnel to perform their work. As a result, areas with limited or no activities are not cooled, allowing for energy efficient mining operations (Greyling, 2008 and van Eldik, 2007).

A traditional method of underground spot cooling is through an air-to-water heat exchanger, or air-cooling car (ACC). Chilled water from either a surface or underground fridge plant is pumped to the designated area where the air is cooled through an indirect heat exchanger. The water is therefore utilised as a heat sink medium to transfer the thermal energy away from the area being spot cooled. The cooling potential of this traditional approach is however a function of both the water flow rate and temperature, where the temperature is a lower limit, i.e., air cannot be cooled below this temperature. Therefore, the water temperature needs to be substantially lower than the air to provide effective cooling. This cannot always be guaranteed for underground mining operations due to the vast depths and distances to remote working areas in modern mining operations and insulation difficulties (Potgieter & van Eldik, 2017).

Another spot cooling method implemented makes use of a mobile vapour compression refrigeration unit, referred to as an Air-Cooling Unit (ACU), where water is also utilised as a heat sink. An attractive attribute the vapour compression refrigeration cycle is that cooling can be deliver over a significantly large heat sink range. An ACU can cool air to temperatures lower than that of the incoming cooling water, which is not achievable with a conventional ACCs, and furthermore, eliminates or reduces the central cooling infrastructure requirements (Greyling, 2008).

However, the efficiency of ACU operations depends on the water availability. Within a varying service-water availability environment, both the kilowatt hours air cooling delivered as well as the cost of operations can be negatively influenced.

This paper demonstrates the importance, and therefore, operational advantage when an ACU, as opposed to an ACC, is used where mine service-water is utilised as a heat sink. The ACC’s ability to perform air-cooling while utilising mine service-water as heat sink is compared to that of an ACU. This includes water temperatures where the ACC fails to deliver a safe working environment. Furthermore, the operational constraint of varying service-water availability is addressed to maximise spot cooling potential. Improved screw compressor control is incorporated and demonstrated through a case study, where spot cooling is maximised through increased kilowatt air cooling provided, together with lower operational unit costs.

Note that for the remainder of this paper, *mine service-water* will only be referred to as *water*.

2 SPOT COOLING: A COMPARISON OF TECHNOLOGIES

Apart from equipment capacity sizing, the two largest influencing factors of underground spot cooling capacities are the supply water mass flow rate and temperature. The water mass flow rate is an indication of the ability to transport extracted heat away from the area being cooled. The supply water temperature is an indication of the ability to absorb heat. This difference between the two technologies follows.

A cooling car operates on the principal of direct heat extraction from a warmer (air) to a colder (water) medium. Warm air is forced to flow over a heat exchanger with water inside finned tubes, where the fluids are thus not in direct contact. If the cooling water temperatures are by some margin lower than that of the air, the cooling of air will be achieved. For a cooling car to be effective this temperature difference, or *the pinch*, must be as small as possible to increase the effectiveness thereof. Alfa Laval (Pty) Ltd (https://www.alfalaval.com/microsites/increase-efficiency/products/compact-heat-exchangers/) claims that its compact heat exchangers can transfer heat for a pinch as low as 2°C. This, however, will typically not be possible within a dusty underground mining environment.

The interpretation of a pinch is as follows; state that air must be cooled down to at least 25°C, via a cooling car and that a pinch of 2°C is possible. For air cooling to occur, the water that enters the cooling car may not exceed a maximum temperature of 23°C. Higher water temperatures will still allow for air cooling, only to a minimum of 2°C above the available water temperature. Therefore, if the available water temperature is 30°C, the air can only be cooled down to 32°C.

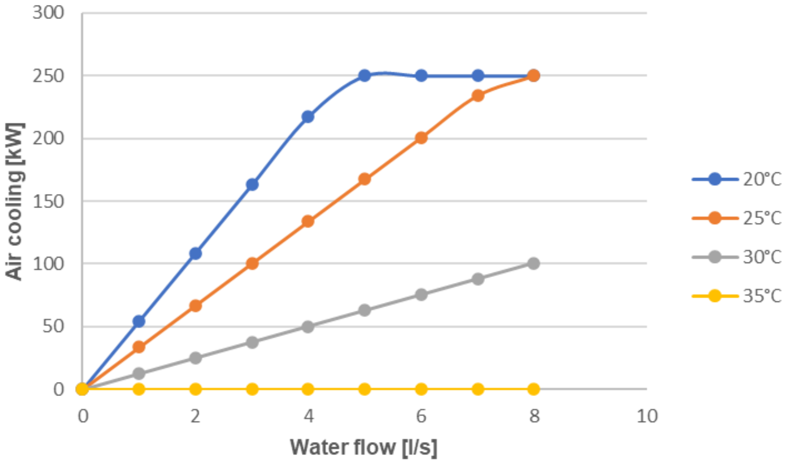

Figure 1: ACC cooling rates at water temperatures and - flow rates for dry-bulb air temperatures at 80% relative humidity.

The ACU evaluated can provide a rated cooling of 250 kW, i.e., at full capacity 250 kWh of heat can be extracted from the air in one hour for dry-bulb temperatures up to 40°C and a relative humidity of 100%. The paper will therefore use this 250 kW as a basis, and for a comparison use a 250 kW ACC with a pinch of 2°C.

Assume now that air at 36°C (dry-bulb) and 80% humidity needs to be cooled. Figure 1 demonstrates the air-cooling rates that are possible for different water temperatures over a range of mass flows when a cooling car is used with a pinch of 2°C. Note that when water is at 20°C, approximately 5.0 l/s is required to deliver 250 kW air cooling; at 25°C 8.0 l/s is required and 30°C can only deliver 100 kW air cooling. Further note that no cooling is possible when water flow rates are at 35°C.

Figure 2 provides the air cooling rates for an ACU under the same water flow conditions as in Figure 1. It can be seen in Figure 2 that at 20°C, the ACU provides less cooling per water flow rate; however, slightly better cooling rates are obtained at 25°C. Note how the full capacity cooling is still achieved when water is at 30°C and almost 90% (220 kW) is possible at 35°C (dry-bulb).

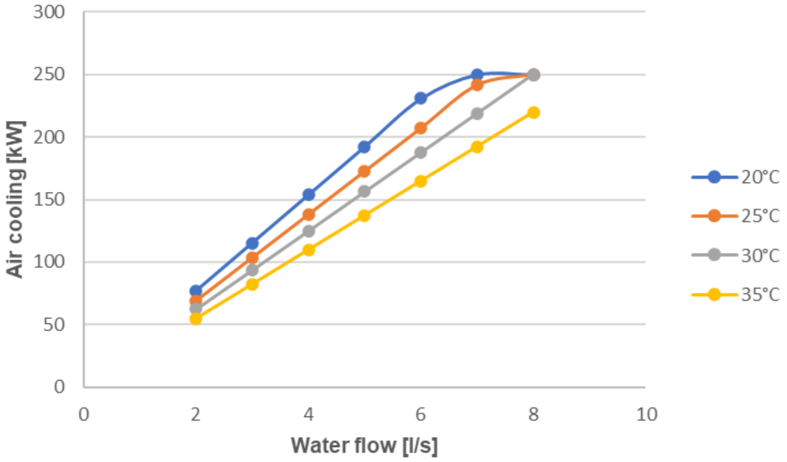

Figure 2: ACU air cooling rates at water temperatures and flow rates for dry-bulb air temperatures at 80% relative humidity.

From Figures 1 and 2 it is evident how the ACU outperforms the traditional ACC under high water temperature conditions. Table 1 provides the minimum dry-bulb air temperatures that can be achieved by both ACC and ACU under the water temperatures depicted in Figures 1 and 2. Note, even though the cooling car can provide approximately 40% (100 kW) air cooling for 30°C water, the minimum achievable temperature is only 28°C (dry-bulb), i.e., a pinch of 2°C. The ACU, however, can provide 23°C (dry-bulb) air temperatures for up to 30°C water temperatures under 35°C (dry-bulb) ambient conditions. Water at 35°C can achieve air cooling down to 24.2°C (dry-bulb).

Table 1: Minimum achievable air-cooling temperatures for ambient air at 35°C (dry-bulb).

Water temperature (°C)	ACC (dry-bulb)	ACU (dry-bulb)
20°C	22.0°C	23.0°C
25°C	23.0°C	23.0°C
30°C	28.0°C	23.0°C
35°C	35.0°C	24.2°C

Note from Figure 2 that the ACU only provides air cooling from 2.0 l/s and higher, whereas it can be seen in Figure 1 that an ACC can provide air cooling for any water flow rate above zero.

3 OPERATIONAL CHALLENGES FACED BY THE ACU

3.1 *Real life case study comparison*

This section provides two real-life case studies, i.e., Case study I and Case study II. Case study I demonstrates unique challenges that are faced by an ACU that operates under varying water flow availability. Case study II demonstrates ACU operations where improved compressor capacity control is implemented. From Case study II, the inefficient operations from Case study I can be understood, as well as the operational improvements under improved compressor capacity control. These operational improvements include increased air cooling delivered in terms of kilowatt hours, at lower operational costs.

3.2 *Case study I: four step control compressor operations*

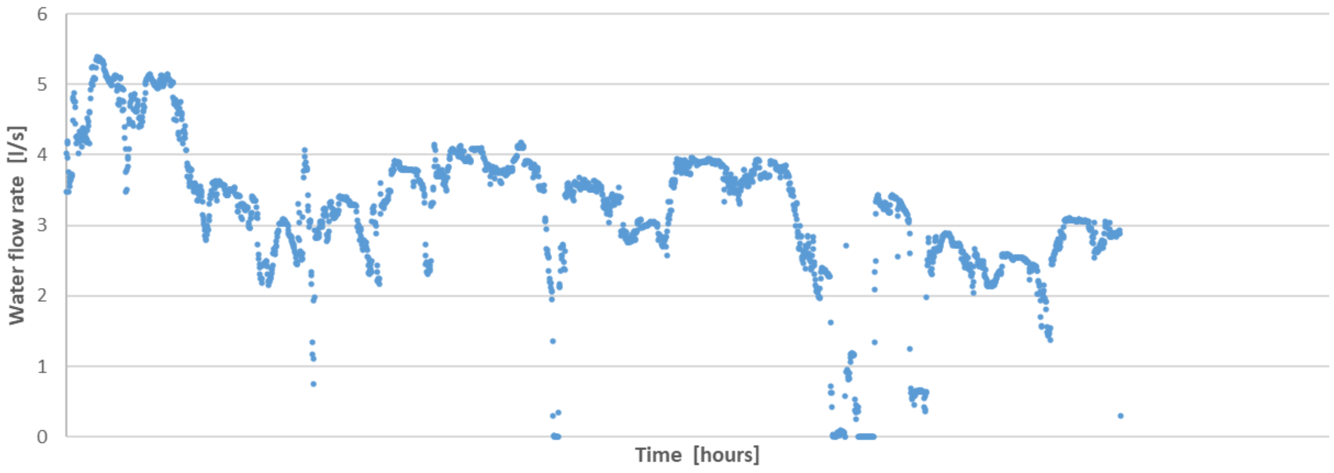

Figure 3: Supply water flow rate over time for Case study I

The water flow profile of Case study I is depicted in Figure 3, where water temperatures varied between 20°C and 22°C. This is a typical, and therefore, not uncommon varying water profile that is experienced by ACUs during operation. From Figure 2 it is both evident that different water flow rates result in different air-cooling rates, and that the unit cannot operate when water flow drops below 2.0 l/s. For water flows below 2.0 l/s the ACU must shut down to protect both the compressor and its motor. This is due to an excessive increase in discharge pressure resulting from the inability of insufficient water flows to remove required heat from the condenser. During these periods of unit shut down no air cooling can be provided, which is a concern for continuous mining operations.

Important to note is that in Case study I, the compressor functions under four step-control operations, i.e., 25%, 50%, 75% and 100% of full capacity. As a result, when water flows vary as seen in Figure 3 the compressor settings will change to try and keep the unit operational but prevents the cycle to operate optimally, and at times the unit will shut down when operations is lower than the 25% setting. Due to the step control for certain periods the unit performs at lower efficiencies, so that either less air cooling is provided, or equivalent cooling at higher operational costs are experienced.

Figure 4 displays the electrical current following the water flow profile depicted in Figure 3. Although the water flows fell below 2.0 l/s at times as can be seen in Figure 3, the non-operational instances do not align with only flows below 2.0 l/s. These events are typically when low, but above 2.0 l/s water flows reduced too fast, so residual heat built up in the vapour compression cycle, even though the compressor was at stepped down to 25% capacity. As a result, unnecessary shut down events occurred due to low flow water variability.

Table 2 provides the cooling COP of the ACU operating under varying water flow conditions, as depicted in Figure 3. Note that for steady state design conditions the cooling COP of an ACU that operates between 5.0 l/s and 6.0 l/s should be 3.3 for the current temperature range (20°C to 22°C), as opposed to 2.5 in Table 2.

A solution to improve the performance is for the supply water flow rate to be stable within the design specification of the ACU. Water, however, is a scarce resource, and furthermore, the availability thereof for underground mining depends on numerous factors, which include infrastructure and shift operations. It is typically not viable to request stable and sufficient water flow availability as it is difficult for the mine to control. Therefore, an alternative solution is required for the ACU to stay operational under varying water flow availability.

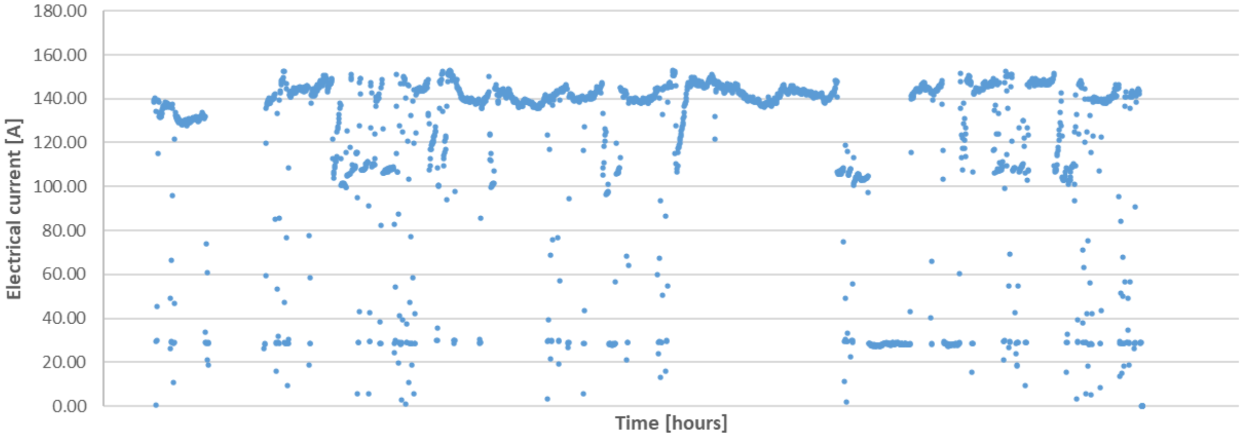

Figure 4: Electrical current over time for Case study I.

Table 2: Cooling COP at different water flow rate intervals for Case study I.

Water flow rate [l/s]	COP
2 l/s to 3 l/s	2.0
3 l/s to 4 l/s	2.1
4 l/s to 5 l/s	2.3
5 l/s to 6 l/s	2.5

3.3 *Case study II: improved stepless compressor capacity control*

There can be stepless capacity control on the screw compressor slide valve mechanism where the discharge pressure is controlled within a small interval, i.e., near constant, so that the compressor step-up or step-down is automated, and not controlled in fixed steps as in the previous section. Case study II is for an ACU where the screw compressor operates with a stepless capacity controller.

Figure 5 displays water flows for Case Study II's ACU and Figure 6 its electrical currents. Further note that flow variability is more prominent in Figure 5 when compared with Figure 3. The expectation would be that cooling COPs based on ACU operations without a stepless capacity controller under Figure 5 will not be an improvement when compared to those provided in Table 2.

However, Figure 6 depicts the electrical currents with the varying water flows of Figure 5. Note the less 'scattering' of data points in Figure 6 as opposed to Figure 4. This is an indication of fewer shutdowns that were experienced by the ACU in Case study II with higher water flow variability as opposed to Case study I. The cooling COPs for Case study II's ACU are provided in Table 3.

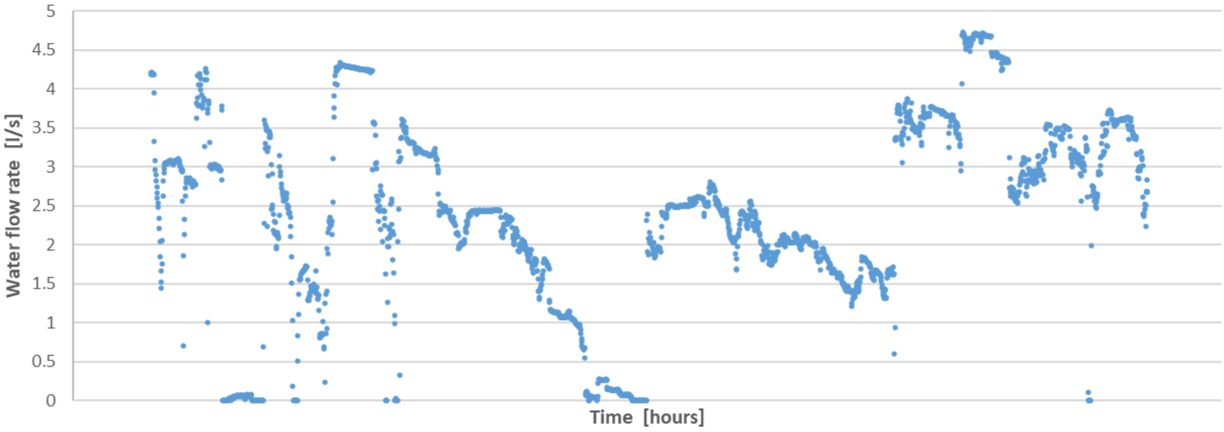

Figure 5: Supply water flow rate over time for Case study II

Note from Table 3 how the cooling COPs, and therefore, the cycle efficiency is constant over the range of water flows, despite the variability thereof. This is due to the stepless capacity controller that allows the compressor to operate at a near constant discharge pressure. As a result, the unit operating in Case study II operates at more efficient levels than the unit from Case study I. Further note that the water profile in this case never exceeded 5.0 l/s, so that cooling COP information cannot be provided for this instance.

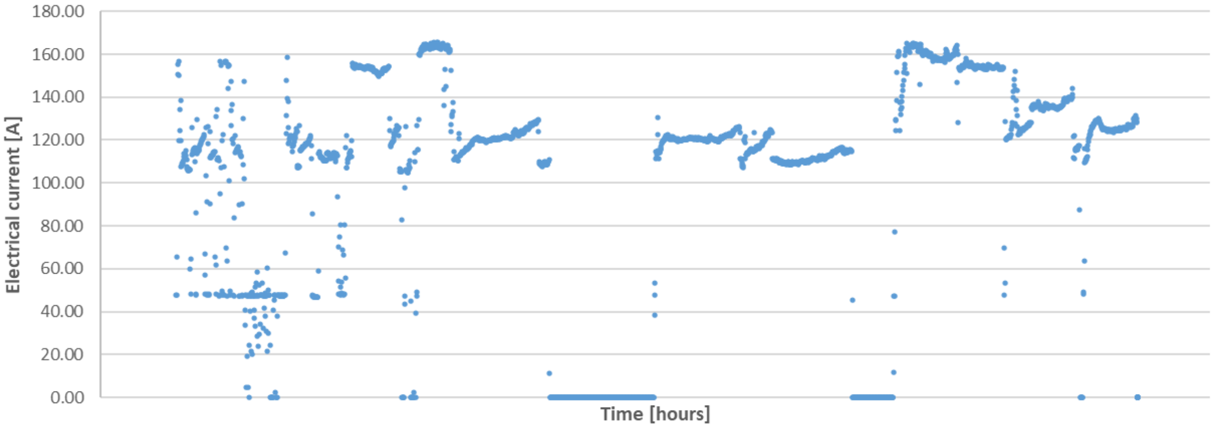

Figure 6: Electrical current over time for Case study II.

Table 3: Cooling COP at different water flow rate intervals for Case study II.

Water flow rate [l/s]	COP
2 l/s to 3 l/s	3.3
3 l/s to 4 l/s	3.3
4 l/s to 5 l/s	3.3

3.4 *Kilowatt hour cooling and electrical cost comparison between Case studies I and II*

For Case study I, an average hourly air cooling of 196.5 kWh was achieved, while the screw compressor power usage was 93.3 kWh (COP=2.1). It follows from a developed simulation model that if the unit was to be operated with a stepless capacity controller under the same water profile, an average hourly air cooling of 223.4 kWh could possibly have realised at an electrical power input of 67.3 kWh (COP=3.3). Therefore, the capacity controller would have resulted in a 13.7% increase in the air-cooling rate, together with a 17.8% reduction in electrical power consumption per kilowatt hour of cooling delivered.

Note that for power consumption only the refrigeration cycle was considered, which excluded all auxiliary operational costs that include the air fan.

4 SUMMARY AND CONCLUDING REMARKS

This paper discusses the ability of a spot cooling ACU to provide a safe working environment for underground mining where centralised air conditioning is either not possible or practical, or where water temperatures are too high for conventional ACC utilisation. Operational challenges in terms of varying water flows were further discussed as well as the reduced operational efficiency and less air cooling that may occur.

A compressor capacity controller was implemented as a solution that allows the ACU to operate at higher air-cooling levels, together with increased energy efficiency operations. A simulation based on data analysis models indicated that an ACU operating with a stepless capacity controller for the compressor could have provided 13.7% more air-cooling, at an electrical cost reduction of 17.8% per kilowatt hour cooling provided compared to a step control approach.

5 REFERENCES

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