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Heat stress management in underground mines

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ABSTRACT

Heat management must be maintained within the mine working environment to minimize stress on equipment and personnel. The issue is a growing concern as mines continue to expand in size, depth and infrastructure. Heat management is a concern as it relates to both heat sensitive equipment and more importantly the health and safety of the workers found within the mine. Proper application of engineering protocols and work practice controls will have a direct impact on the health and safety of workers and increased productivity. Using continuous monitoring stations placed in strategic locations throughout the mine to capture the environmental conditions, various strategies can be used in the planning and prevention of potential hazard exposure. Economic analysis is used to select the most feasible strategy for heat stress control. This paper presents a step by step methodology that may be considered by ventilation specialists to effectively implement a heat management control system. A case study based on a detailed heat management assessment conducted for a potash mine in Saskatchewan, Canada is presented.

1. Introduction

Heat stress can affect individuals with a range of ill effects, compromising the ability for an individual to cool oneself. Factors influencing the severity of heat stress may include the workers age, fitness level and overall health. Additionally, the effects of heat stress can range, in order from least to most dangerous, from heat rashes, heat cramps, heat exhaustion to heat stroke–the latter being the most dangerous with the highest risk of death. Heat stroke occurs when the body's internal temperature rises above 40 °C [1].

There are many different heat sources that contribute to hot environmental conditions underground. These factors may be greatly increased or decreased based on the mine and mining methods used. Some common sources of heat may include auto compression or adiabatic compression, geothermal gradient, blasting, electrical and diesel machinery, human metabolism, oxidization of the orebody or timber, and ground movement [2]. The geothermal gradient with deep mines is often the greatest contributor to the overall hot conditions as the virgin rock temperature increases with depth [3]. The virgin rock temperature surrounding the excavations has a significant role of the ambient air temperature throughout the mine, however electrical and mechanical infrastructure may have varying additional impacts on the conditions spread out across the mine workings. These effects of the heat sources on the environmental conditions ultimately may have substantial impacts in both local excavations and workings found throughout the mine, which must be considered and evaluated.

Heat management is an important factor as mines expand to meet the demand of their growing workforce and extraction rates. The introduction of new equipment and manpower puts additional demands on the ventilation system that is often the primary means of heat control. When mines plan to place additional significant heat sources into the ventilation system, the proper methodology used to monitor, establish and control heat stress with economically viable solutions must be established. The methods used to control environmental conditions within the mine workings need to be both economically viable and feasible. A review of alternatives for cooling ultra-deep mines in Northern Ontario and Quebec, lays out a variety of options that could be implemented within mines experiencing heat stress conditions, which captures capital expenditures and maintenance costs of the systems [4]. Cooling method technologies include ice slurry systems, cooling tower, bulk air cooling, spot coolers, among others. The opportunities and costs of these methods must be thoroughly understood before a mine can implement a heat management program.

This paper presents a step by step methodology for (1) identifying heat sources, (2) establishing a heat monitoring program, (3) calculating heat loads underground, (4) applying heat management strategies and (5) comparing and selecting engineering solutions to heat control.

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A detailed case study, based on a heat stress management study conducted for an underground potash mine, is presented to illustrate application of the proposed strategy.

2. Heat management methodology

A proposed methodology for establishing a heat management program is presented. In the methodology, heat sources are identified, data is collected from environmental monitoring stations and calculated heat loads are assessed using ventilation modeling software. Application of specific management control strategies allows one to control or eliminate heat stress and improve safety.

2.1. Identification of heat sources

All heat sources within the area of interest must be identified and quantified in terms of heat load. The virgin rock temperature is a critical factor in assessing heat loads on the system. The geothermal gradient may provide enough details to accurately describe the surrounding rock temperature. An effective way to measure the virgin rock temperature may be through drill hole data collection [5]. Drill holes are extended a minimum of 10 m into the rock strata at various locations. Thermocouples installed and insulated at depths along the drill hole collect data for analysis. As the temperature levels stabilize with depth, a virgin rock temperature may be determined. To identify heat sources in an area of concern, a survey of the equipment found must be completed. Electrical infrastructure, including power lines and transformers, may be assessed through their resistances and efficiencies to determine heat losses [6,7]. Additionally, stationary equipment and mobile equipment will also have a rated efficiency, which allows for the calculation of heat lost to the atmosphere by identified heat sources.

2.2. Establishment of a heat monitoring program

There is a wide range of environmental monitoring programs that are commonplace throughout the mining industry. Mining regulations typically set minimum standards regarding the monitoring and recording of the environment factors relating to heat found within the underground environment. The basic method frequently employed is the use of handheld monitoring equipment, which is checked and recorded at predetermined locations and on a set schedule. Additional monitoring often only occurs as the result of a change to the ventilation conditions. This type of monitoring often presents a level of accuracy that is sufficient to meet regulatory requirements, but may not provide enough detailed information to account for fluctuating conditions that can range from acute cases to seasonal in nature. When an area within the mine is identified as a potential hazard from heat accumulation, additional monitoring is required. This is done to ensure that the areas the workers are entering are well-managed to minimize heat stress exposure. Additionally, if there is heat sensitive equipment, reducing the environmental heat conditions will often promote equipment function as well as extend equipment life. To capture enough information to accurately describe the conditions found within the subject area of concern a minimum monitor recording frequency must be met based on potential daily and in some cases hourly fluctuations. Currently there are several stand-alone environmental monitors that can be set to monitor conditions at intervals set by the user and placed in the field for real time observation and data collection.

2.3. Calculating heat loads underground

In order to assess the heat load within the underground environment, there are different methodologies that may be employed in order to use the appropriate heat management technique. Heat stress is often considered as a factor of the wet bulb globe temperature when considering the effects of heat on the workers in the mine.

Wet bulb globe temperature (°C) WBGT, can be calculated within the mine environment with the following equation;

$$\text{Web bulb globe temperature} = 0.3t_{gt} \times 0.7t_{wb} \tag{1}$$

where t_{gt} is the globe temperature, °C; and t_{wb} the wet bulb temperature, °C.

To assess the energy that is contained within the air in the underground environment, the enthalpy of the system can be calculated, which considers the moisture content of the air. Additionally, the sigma heat can also be calculated, which considers the energy content less the moisture content. Both methods used to describe the energy contained within the air are considered on a dry basis (kJ/kg dry air).

In order to calculate the enthalpy of the system, the enthalpy of the air (kJ/kg) (h_a) and the enthalpy of the vapour (kJ/kg) (h_v) must be combined [8].

$$h = h_a + h_v = 1.005t_{db} + W(2501.6 + 1.884 \times t_{db}) \tag{2}$$

In order to calculate the apparent specific humidity (kg/kg dry air) the following equation must be used:

$$W = 0.622\frac{P_s}{P_b - P_v} \tag{3}$$

$$P_S = 0.6105\exp\left(\frac{17.27 \times t_{db}}{237.15 + t_{db}}\right) \tag{4}$$

$$P_v = P_S - 0.000644 \times P_b(t_{db} - t_{wb}) \tag{5}$$

In the above equations, t_{db} is the dry bulb temperature, °C; P_s the saturation vapour pressure, kPa; P_b the barometric pressure, kPa; and P_v the vapour pressure, kPa.

The enthalpy can then be applied to the mass flow (M_f) to find the heat flow (Watt) (q_f) in the system. The following calculation assumes not change in moisture to the system.

$$q_f = M_f(\Delta h) \tag{6}$$

$$M_f = Q \times w \tag{7}$$

where M_f is the mass flow, kg/s; Δh the sigma heat change, kJ/kg; Q the flow rate, m^3/s; and w the air density, kg/m^3.

In a ventilation system where there is a change in moisture the heat flow can be found using the sigma heat on a dry basis (S).

$$q_f = M_f(\Delta S + B) \tag{8}$$

$$S = h - 4.187 \times W \times t_{wb} \tag{9}$$

where B is a term which depends on the process involved and on the change in moisture content, °C^{-1}.

Another method of calculating heat loads within the mine environment is by calculating the heat load losses, based on equipment found within the excavation of concern. This method is useful for both reactive heat management planning and predictive heat management. In order to assess the heat losses from equipment, a detailed equipment survey must be conducted on the equipment found within the area of concern. This includes the stationary and mobile equipment, the infrastructure used to power the system, and the utilization of the components within the area. It is advisable to break down the area of concern into smaller segments based on changes in features contained within the excavations, or physical changes in the excavation itself. The strata surrounding the excavation and the changes in moisture content can also have

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significant impacts on the heat load prediction based on equipment heat losses, so it is important to understand the behavior of the rock type as well as any significant changes in moisture content within the excavations. This process is described in Section 3.

2.4. Applying heat management strategies

The application of a heat management strategy will serve to limit the level of health risk associated with the total heat load imposed on a worker underground. Heat management strategies include refrigeration (bulk air cooling), localized refrigeration (spot coolers), ventilation, administrative controls (air conditioned cabins, cooling vests, acclimatization, rest areas), and engineering controls (controlling/reducing heat at source, shielding, insulation).

Heat stress avoidance and using work-rest schedules may be implemented to reduce exposure to heat stress conditions for long periods of time. In some jurisdictions, the standards are prescribed within Labor Standards or Mines Regulations [9]. In some cases, acclimatization may also be used as a heat stress avoidance method. Slowly acclimatizing workers to heat stress conditions under a controlled environment has been proven effective in some South African mines [10]. This method, like the avoidance method is costly in relation to the reduction of production time as the body requires time to acclimatize to the conditions and exertion of energy. However, this may be offset by the low cost of implementation.

2.5. Comparing and selecting engineering solutions for heat control

Selection of the ideal solution for heat control requires an engineering and economic analysis of alternatives. The solution is more likely a combination of strategies and available technologies. The combined application of engineering and administrative controls, together with selected work practices is effective means of reducing excessive heat exposure.

3. A case study

3.1. Area of study

A management program of heat generated from pumping infrastructure in a Saskatchewan potash mine has been established. The study area is 5.6 km of underground excavations within series ventilation and recirculation circuits. There are over 20,515 kW of electric motors resulting in 305,000 W of lost energy to atmospheric heat. In addition to these motors there are 49.6 km of electrical power cables and the associated electrical controls and transformers, which also lose energy to heat throughout the area.

3.2. Identification of heat sources

In order to identify the locations and sources of heat, the study area was broken down in 14 zones shown in Fig. 1. Zone allocation was based on a number of attributes, including the number of people expected to work in different areas in a work day, ventilation attributes, and infrastructure features. Pumping clusters are located within zones 2, 5, and 7; electrical clusters, which includes the transformers and electrical sleds which power the pumps, are located in zones 1, 4, 7, and 12. The remaining zones include limited equipment, with electrical equipment and cables running through the study area in its entirety. Each zone was further broken down into 20 m sections to be used for future computational modeling. Within each section the heat source components were identified. The Heat Management Study Area and zone locations are identified in Fig. 1. The primary sources of heat include strata, electrical cable, transformers, motors and settling tanks.

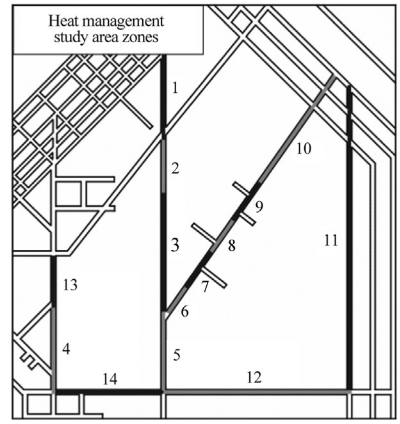

Fig. 1. Heat management study area.

3.3. Monitoring program

In the case example used within the potash mine, due to the relatively close proximity to the incoming shaft air, there are hourly fluctuations in air properties as a result of changes to the surface temperature supply air. As a result of the required high frequency of recordings, a network of environmental monitoring stations was essential in order to capture the characteristics of the air as it moved throughout the study area. The installation of 22 Accutron Climatrax stations in conjunction with data loggers allowed for the monitoring of the following environmental factors: dry bulb temperature, wet bulb temperature, relative humidity, and barometric pressure. These parameters are then applied to determine all required pyschrometric properties.

To determine regional changes within the study area, selecting the appropriate locations to monitor was critical. The study area was broken down into zones that were considered heat source areas and heat sump areas. Observing the areas that had the greatest impact on the area allows for targeting of heat control applications. In addition to the supply air, the surrounding stratum also has an impact on the environmental conditions. To better observe the rock behavior on the air, it was necessary to capture the transfer of heat both into and out of the rock as it behaves as both a source of supply and removal of heat. In order to do this, heat fluctuation plates were installed against the strata to monitor the transfer of heat in and out of the rock. To further improve upon the observation of the rock characteristics, the virgin rock temperature can aid in the identification of the limits to which the rock can act as a source or sink of heat. In the study of the potash mine, 15.25 m long vertical and horizontal bore holes were established to capture this information. Temperature probes were located at 1.5, 3, 6, and 15 m to monitor heat fluctuations with depth.

3.4. Heat load calculations

To calculate the energy lost to the atmosphere as heat, the efficiency of the equipment was calculated at full load and continuous use. This was applied to all sources of heat except for the electrical cables, which are based on 60% of full load. The primary sources of heat energy result from losses with transformers and pumping equipment. The estimated flow of heat for each zone is summarized in Table 1.

Survey data was collected at the beginning and end of each zone to calculate the change in enthalpy and sigma heat for each zone. The data that was required to do the calculations included: dry

Table 1
Summary of heat load study.

Area number	Total loss (W)	Total loss (BTU/h)
1	187,435.5	639,556.6
2	202,534.2	691,075.5
3	35,620.01	121,541.0
4	82,022.8	279,873.4
5	6,710.6	22,897.6
6	129,160.3	440,713.1
7	224,794.4	767,030.4
8	17,166.5	58,574.5
9	150,918.0	514,953.6
10	485,040.0	2,227,047.1
11	20,239.0	69,058.4
12	10,212.1	34,845.2
13	10,815.3	36,903.3
14	19,789.0	67,522.7
Total heat loss	1,582,457.88	5,971,592.33

bulb, wet bulb, relative humidity, pressure, and density. The environmental monitors that were set up within the areas were programmed to record this data on a 10 min interval that could then be averaged at intervals that best suited the needs of the mine. This data could then be used to calculate the heat loads within the system, summarized in Table 2.

3.5. Heat management strategy application

In order to manage the heat produced within the workings, there are two goals that should be met. Firstly, minimizing heat stress conditions to personnel, and secondly reducing heat exposure to equipment.

In order to minimize heat stress conditions to personnel, a work plan that decreases work in high wet bulb globe temperatures according to heat stress guides may be a viable option. The heat stress guide listed in Table 3, outlines working time lengths and job type that can safely be performed based on the environmental conditions. There are limitations to this type of heat management plan, as it does not lower heat exposure to heat sensitive equipment and may not be economically or practically feasible based on the length or type of work being performed.

A second option may be setting up spot cooling within the workings to remove the additional heat produced by the equipment. In the case study the location that would see the largest local benefit and to air traveling downstream is zone 2.

In order to set up a cooling plant in zone 2 the following parametric design was conducted.
The mass flow (M_f) entering zone 2 is 29.6 kg/s.
The specific humidity entering zone 2 (W_1) is 0.025 kg/kg.
The enthalpy entering zone 2 (h_1) is 95.04 kJ/kg.
Air is to be cooled to 27.8 °C.
Using a psychometric chart and 27.8 °C as the chosen output, the following outgoing enthalpy and specific humidity were found.
The specific humidity leaving zone 2 (W_2) will be 0.20 kg/kg.
The enthalpy leaving zone 2 (h_2) will be 78 kJ/kg.
The specific enthalpy of water (h_{w2}) at 27.8 °C is 123.5 kJ/kg.

By installing the temperature probes into the rock, the ambient virgin rock temperature of both the salt and potash members were found to be 27.1 °C, this is the lower limit of the attainable cooling before the rock becomes an additional heat source for the excavation, limiting the effectiveness of the cooling.

The cooling load requirement (Q) can be found using

$$Q = M_f \times [(h_1 - h_2) - (W_1 - W_2) \times h_{w2}] \tag{10}$$

The resultant cooling load is 489 kW or 139.2 tons of cooling by an installed cooling plant.

With the installation of a chiller plant within the underground environment, the cost of the plant must be taken into consideration. The initial capital expenditure is the upfront cost, but the cost of operation should be assed. The cooling plant efficiency can be assed based on the coefficient of performance (COP). This allows a basic assessment of the cost of running the plant.

A typical cooling plant that could be used within this location is a water cooled electrically operated positive displacement cooling plant. According to energy design resources the COP for this type of plant, would be approximately 4.20. The energy requirements to run the plant would be

Table 2
Survey data.

Location	Dry bulb (°C)	Wet bulb (°C)	RH (%)	Pressure (kPa)	Density (kg/m^3)	Ps (kPa)	Pv (kPa)	W (kg/kg dry air)	Cp (kJ/kg)	h (kJ/kg dry air)	S (kJ/kg dry air)
1 in	32.9	20.7	33	107.8	1.21	5.0053877	4.158425	0.025162215	1.052405613	97.57	94.10
1 out 2 in	33.5	21.1	33.3	107.8	1.23	5.1765363	4.315689	0.026157355	1.054280456	100.75	97.08
2 out 3 in	37.4	22.7	28.6	107.7	1.23	6.417911	5.398337	0.033152608	1.067459513	122.86	117.67
3 out	31.7	21	38.4	107.8	1.23	4.6777726	3.934944	0.023734315	1.049715499	92.65	89.50
4 in	28.1	19.7	45.6	107.9	1.23	3.8040593	3.220363	0.019242499	1.041252868	77.40	75.13
4 out	29.6	19.8	41.3	107.8	1.23	4.1491112	3.468764	0.020815751	1.044216875	82.98	80.40
5 in	29.5	19.3	38.7	107.8	1.23	4.1252894	3.417173	0.020501446	1.043624724	82.07	79.54
5 out	29.8	19.5	38.4	107.8	1.23	4.197114	3.482055	0.020905192	1.044385382	83.42	80.81
6 in	30	19.6	39.4	107.8	1.23	4.245599	3.523598	0.021164507	1.04487393	84.29	81.63
6 out 7 in	32.3	20.1	32.6	107.8	1.23	4.839173	3.99221	0.024117469	1.050437312	94.26	91.00
7 out 8 in	32	20.4	35	107.7	1.22	4.7578784	3.953316	0.023886847	1.050002821	93.36	90.15
8 out 9 in	31.7	20.3	35.3	107.8	1.22	4.6777726	3.886348	0.023441198	1.049163217	91.90	88.79
9 out 10 in	32.9	20.9	33.8	107.7	1.21	5.0053877	4.173082	0.025275494	1.052619031	97.86	94.38
10 out	34.1	21.3	31.9	107.7	1.21	5.3527408	4.464948	0.027135048	1.05612243	103.89	100.02
11 in	30.9	19.9	36.2	107.7	1.23	4.4698588	3.706912	0.022335524	1.047080126	88.23	85.34
11 out	30.1	19.5	37.2	107.8	1.23	4.2700237	3.534138	0.021232823	1.045002639	84.57	81.89
12 in	30.1	19.5	37.1	107.8	1.23	4.2700237	3.534138	0.021232823	1.045002639	84.57	81.89
12 out	29.5	19.4	38.4	107.8	1.23	4.1252894	3.424115	0.020543097	1.043703194	82.18	79.64
13 in	31	20.5	36.9	107.8	1.23	4.4954007	3.766457	0.022677948	1.047725254	89.21	86.27
13 out	31.8	20.6	36.9	107.8	1.23	4.7043434	3.926804	0.023691316	1.04963444	92.64	89.49
14 in	29.2	19	38.2	107.8	1.23	4.0545363	3.34642	0.020063268	1.042799196	80.64	78.19
14 out	28.1	19.7	45.6	107.9	1.23	3.8040593	3.220363	0.019242499	1.041252868	77.40	75.13

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Table 3
Wet bulb globe temperature index [11].

Work load	Work rate			
	Continuous	15 min rest per hour	30 min rest per hour	45 min rest per hour
Heavy	Up to 25 °C	25 °C up to 26 °C	26 °C up to 28 °C	28 °C up to 30 °C
Moderate	Up to 27 °C	27 °C up to 28 °C	28 °C up to 29 °C	29 °C up to 31 °C
Light	Up to 30 °C	30 °C up to 30.6 °C	30.6 °C up to 31.4 °C	31.4 °C up to 32.2 °C

$$Energy\,requirement_{cooling\,plant} = \frac{\text{cooling capacity requirements}}{\text{COP}} \tag{11}$$

which results in 116.4 kW of energy required to run the plant. The annual cost of operation can then be calculated based on continuous operation at the cost of delivery and kWh usage. The cost of continuous usage at this mine for the case study is 0.065 $/kW h.

$$cost_{cooling\ plant} = energy\ requirement_{cooling\ plant} \times energy\ cost_{continuous\ usage} \times run\ time \tag{12}$$

As a result, the annual cost of running a cooling plant in this location will be $66,278.

It is also possible to estimate the cost of cooling any future additional equipment to the area. Based on the equipment survey, a common motor that is used within zones 2, 7, and 10 has a heat loss of 15 kW based on motor efficiency. Using the same principle the cost of cooling additional motor installs would approximate $8,541 per motor. This would allow for the estimate of the additional cost of cooling the zones as additional equipment is added.

4. Conclusions

Heat management plans are growing in importance when it comes to the health and safety of the workforces in underground mines. There are strategies that can be used to minimize the effects on both people and equipment, but the costs of the plans must be realized. There are costs associated with both the efficiency of the work being done because of the heat conditions through avoidance. There are also costs that occur as the result of actively attempting to cool the working areas. These costs must be understood and assed to achieve the greatest impact on the environmental conditions within the mine environment.

A detailed case study on management and control strategies of heat generated by electrical infrastructure within a Saskatchewan potash mine has been presented. The case study showed that within the focus area that there are zones with conditions that could lead to heat stress. With the collected data, a decision could be made that allows for immediate action, limiting the exposure to the workforce in identified areas. The workplace can reduce risk by educating the workforce to be able to recognize the hazards of heat stress and implement short term solutions in the avoidance nature and further develop the strategies described within this paper.

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