Implementation of a Heat Management Control System

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A detailed case study on management and control strategies of heat generated by electrical infrastructure within a Saskatchewan Potash mine has been developed to limit and minimize worker exposure to heat stress. With known heat energy rates, a number of management strategies have been engineered for estimating operational costs and effectiveness. This paper aims to assist the ventilation engineer in the implementation of a successful heat management control system based on the case study findings.

Introduction

Controlling heat and heat stress exposure to the workforce and heat sensitive equipment in mines is a necessary requirement of many mines as they expand in both depth and size. The ability to quantify the heat energy within the ventilation networks allows the ventilation engineer the opportunity to asses and develop strategies, which can be used to combat hot environmental conditions.

This paper aims to explore opportunities that may be considered by a ventilation engineer as they implement a heat management control system. A case study is presented based on data collected within a potash mine in Saskatchewan, Canada. There are multiple approaches to be considered, all of which must be assessed against their cost of operation, effectiveness of heat control, and overall feasibility. Ultimately there is not one single approach that may be used across all scenarios, but the successful implementation of heat control to best suit the conditions may be selected through both the effectiveness and economic implications.

Environmental Conditions Monitoring

In order for the ventilation engineer to develop a strategy to manage heat and heat stress conditions within the mine, they must have an understanding of the heat flow in the excavations. The sources and sumps of heat must be quantified in the mine network and in all areas of concern. Typical sources of heat within the mine may originate from auto compression of the air in the shaft, heat released from the rock strata, frictional heating of the air, machinery, electrical infrastructure, ground movement, and multiple other sources based on the conditions and mining practices. Heat may also be removed within the mine. The evaporative cooling of air from moisture within the excavation, rock strata that has an ambient temperature below the room air temperature, auto decompression as the air rises within the mine to higher mining levels are all ways that heat may be removed from the air.

In order to capture the data required to measure the environmental conditions, the mining engineer must set up instrumentation to quantify the air flow characteristics. Environmental conditions that should be measured or calculated are as follows;

Dry Bulb (Cº)
Wet Bulb (Cº)
Wet Bulb Globe Temperature (Cº)
Pressure (kPa)
Air Density (kg/m^3)
Air Flow Volume (m^3/s)

With instrumentation that is capable of monitoring the air characteristics the ventilation engineer should begin to break down the heat management area into smaller segments for monitoring. A good practice is to break down the areas of concern into zones, based on characteristics found within each zone of the airflow circuit. For example, part of the excavation that has a number of stationary motors for belt drives or electrical substations within the mine may be broken down into individual zones as they are parts of the ventilation network that contain sources of heat. Alternatively, zones that may contain free standing water or moisture on the walls may be a separate zone as it acts as a location of heat removal. Being able to capture this data is crucial in understanding the environmental conditions found within the heat management area.

Within the potash mine case study, the environmental conditions were monitored using airflow and environmental monitors that were placed strategically throughout the study area ventilation network. The network was broken down based on stationary equipment infrastructure and classified as zones. Zones were also formed based on the airway physical characteristics; lengths of excavations were broken down as the excavation increased or decreased cross sectional size. The case study airflow circuits and zones are presented in Figure 1.

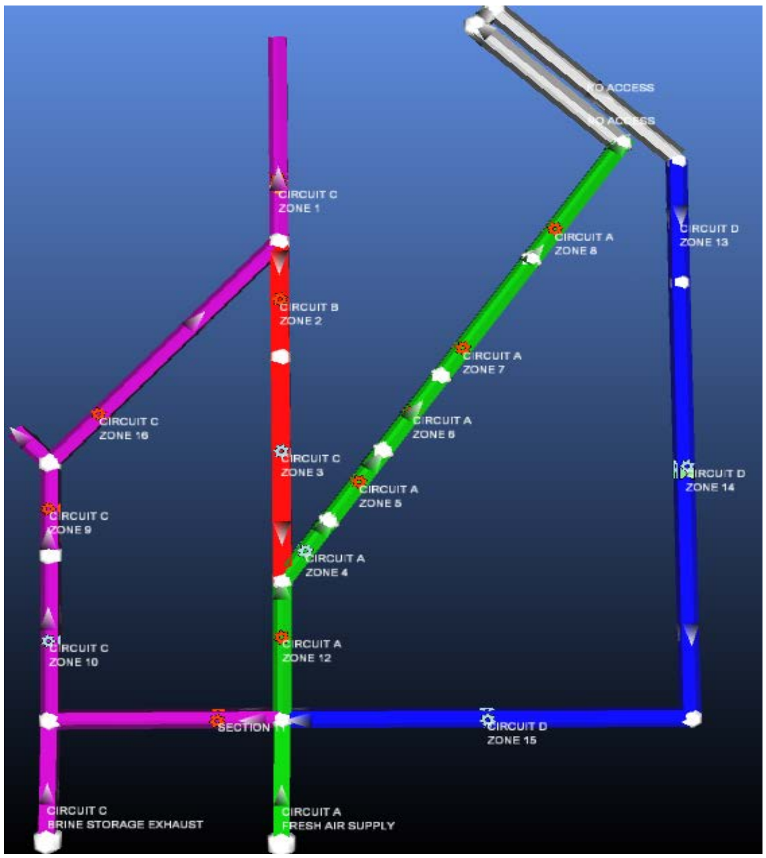

Figure 1- Case Study Circuit and Zone Map

The data should be collected over a period of time that captures a wide range of environmental conditions that may be expected in the heat management ventilation network. The use of data loggers assist greatly in this process. The range of conditions may vary greatly from peak production and maintenance downtime to the seasonal variations that occur in the supply air from fresh air shaft. The case study within the potash mine was allowed to collect data for a period of up to 12 months on an hourly basis in order to capture the greatest expected variations in conditions.

Using the collected data, enthalpies can then be calculated in order to assess the heat content within the air. In order to calculate the enthalpy (h) (kJ/Kg) of the zones, the following equation may be used[1];

$$h = 1.005\ t_{db} + W(2501.6 + 1.884 * t_{db})$$

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

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

Where;

$$P_s = 0.6105\ \exp(\frac{17.27 * t_{db}}{237.15 + t_{db}})$$

And

$$P_v = P_s - 0.000644 * P_b(t_{db} - t_{wb})$$

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

The data collected and analyzed to calculate the heat content and heat stress conditions within the mine, used for heat management assessment purposes at the case study potash mine can be observed in Table 1.

Table 1- Case Study Environment Conditions

Circuit	Zone	Enthalpy (kJ/kg)	Wet Bulb Globe Temperature (ºC)	Mass Flow (kg/sec)	Excavation Characteristics
A	Fresh Air	91-107	20.1-25.3	57	Bare
	12	68-206	20.5-26.3	107	Hanging Cables
	4	90-99	20.9-24.5	145	Electrical Cluster
	5	97-114	22.3-26.4	145	Motor Cluster
	6	103-143	23.4-29.0	145	Brine Sump
	7	105-123	23.7-27.2	145	Motor Cluster
	8	115-181	24.8-34.1	145	Electrical Cluster
B	2	n/a	n/a	38	Motor Cluster
	3	97-127	22.7-28.3	38	Hanging Cables
C	11	n/a	n/a	13	Hanging Cables
	Brine Storage Air	86.9-109.1	19.2-25.3	54	Bare
	10	n/a	n/a	67	Electrical Cluster
	9	107-123	23.9-26.8	67	Electrical Cluster
	16	n/a	n/a	60	Bare
	1	109-169	23.7-31.1	22	Electrical Cluster
D	13	90-118	21.7-26.5	72	Belt Drive
	14	90-115	21.7-26.9	72	Hanging Cables
	15	n/a	n/a	72	Hanging Cables

Management Strategies

Once sufficient data has been collected to satisfy expected conditions, there are a number of management control systems and strategies that can be explored. The use of chiller plants on surface in the headframe is a common industrial standard where conditions permit their use. They can be expensive to operate, but are effective at regulating the incoming air temperature to the mine.

Indirect chiller plants that utilize brine or glycol may also be installed within the mine environment to focus on critical areas. The local plants are smaller than found on surface; however the heat removed and generated through the cooling process must be disposed of. If the ventilation system is not able to handle the heat from a refrigeration plant then a common practice is to pump chilled water from the surface to the refrigeration plant underground, pumping water through a heat exchanger and back to the surface for heat disposal. This is a costly option, found more often in mines with extreme heat conditions.

A less costly option to a refrigeration plant is through changing the ventilation circuit air distribution by mixing flows. The goal is to change the environmental conditions in the areas of concern by reducing the average heat content or temperature. This option works well if there is a significant difference between the environmental conditions of the mixing flows, however one should consider the additional cost associated with the fan power required to redirect and mix the flows.

The use of passive removal of heat via the rock strata may also be used where the virgin rock temperature is significantly lower than the dry bulb temperature of the air. This may be utilized through recirculation or cascading air circuits that reroute air through excavations that can be dedicated for ventilation purposes. This option is viable for mines that maintain open airways, and can be made readily available. Heat transfer from the air to the rock may occur bi-directionally and a detailed understanding of the rock thermal transfer (W/m^2) is required. Fan power to route the air is the significant cost associated with this method, as well as any additional drift development and maintenance that may be required.

In addition to refrigeration and controls there are manpower methods that may be utilized by workers to limit the effects of heat exposure. 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. 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. This method, like the avoidance method is costly in relation to the reduction of production time, in spite of having a low cost of implementation.

The case study at the potash looks at four methods for analysis. The retrofitting of the heating and cooling system within the mine headframe for the fresh air system, the use of spot coolers in the areas of significant heat loads, the use of cascading and fresh air flows to produce mixed flows, and the use of recirculation circuits to passively remove heat via the rock strata.

Head frame Chiller

In order to assess the requirements of the headframe chiller, the local conditions to be expected and the effects of adiabatic compression must be taken into account by the ventilation engineer. The hottest local condition, at the case study mine site in 2015 was 31.1Cº, reached on August 11th. This temperature can then be adjusted by the expected increase in temperature (ΔT) by adiabatic compression, which can be found using:

$$\Delta T = \frac{\text{mass} * \text{gravitational acceleration} * \text{distance}}{\text{specific heat of air}}$$

Where;
ΔT: Change in temperature Cº
Mass: 1Kg of air
Gravitational constant: $9.8 m/s^2$
Distance: 1000m
Specific heat of air: 1005 J/kg Cº

Therefore, the shaft at the mine is 1km in depth, allowing for a dry bulb temperature rise of 9.8Cº under dry conditions.

Assessing the temperature that the cooling plant must be able to obtain can be found by determining the virgin rock temperature underground. Dropping the temperature below the virgin rock temperature, in some cases could be considered a waste of energy. This happens in cases where the cooling effect is not achieved at a great distance from the shaft, because heat energy is drawn from the rock into the air flow until an equilibrium is reached. In the case study, test holes were drilled to a depth of 15m from the working face and thermocouples were installed, insulated and connected to data loggers to monitor the rock temperature. The results of this testing program showed a virgin rock temperature of 27.1Cº, providing the lowest air temperature to be attained within the mine by the installed cooling plant. When the effects of the heating through compression as the air descends is considered, the 27.1Cº is dropped by 9.8Cº to 17.3Cº as the output air temperature of the cooling plant on surface and the basis for the cooling plant sizing (ΔT=31.1-17.3= 13.8Cº).

In order to size the headframe cooling plant requirements ($\mathrm{Q_{cooling\ load}}$) the following equation can be used; [1]

$$\mathrm{Q_{cooling\ load}} = \mathrm{M_f} * [(\mathrm{h_1} - \mathrm{h_2}) - (\mathrm{W_1} - \mathrm{W_2}) * \mathrm{hw_2}]$$

Using psychrometric data for air-water-vapor mixtures to find the cooling load, and the known data collected, the following variables are found;
The mass flow of air (M_f) on surface is 148.0 kg/sec.
The specific humidity (W_1) on surface is 0.026kg/kg.
The enthalpy of the air on surface (h_1) was 97.82kJ/kg.
The air is to be cooled to 17.3Cº.
Using a psychrometric chart and 17.3Cº as the chosen output, the following outgoing enthalpy and specific humidity were found.
The specific humidity W_2 will be 0.010kg/kg.
The enthalpy of the air (h_2) will be 46.5 kJ/kg.
The specific enthalpy of water hw_2 (17.3Cº) is 72.34 kJ/kg.

Therefore, the amount of refrigeration that would be necessary to cool the air to below heat stress conditions during the peak summer months experienced would be 7421.2kW or 2110 tons of refrigeration.

In order to assess the economics of this type of plant the following equation can be used;

$$\mathrm{Cost_{cooling\ plant}} = \mathrm{Energy\ Requirements_{cooling\ plant}} * \mathrm{Energy\ Cost} * \mathrm{Run\ Time}$$

The energy requirements are based on the coefficient of performance (COP) of the plant. Typically a head frame chiller is composed of a brine or glycol positive displacement system. This type of system has an expected COP of 4.2. [2] The energy requirements of the cooling plant can be then found;

$$\mathrm{Energy\ Requirement_{cooling\ plant}} = \frac{\mathrm{cooling\ load\ required}}{\mathrm{COP}}$$

At an expected run time of 135 days, based on historical weather trends and a cost of energy of 0.065$/kWh, the cost of operation of this cooling plant would be $372,119 per year.

Spot Cooler

An alternative option to a headframe chiller is a spot cooling refrigeration system that can be installed in the excavation or excavations that have the greatest need. This both reduces the size of the plant required and targets specific needs at specific locations. The greatest challenge the ventilation engineer is faced with is the heat energy generated to run the cooling plant and the disposal of the heat removed. There are also spot coolers that use latent heat of vaporization to cool the air. These cooling units rely on cooling the air by spraying or dripping water through the air to be evaporated, reducing the sensible heat content in the air. This additional moisture content to the air may also have negative impacts to the overall ventilation system and must be assessed, case by case.

In the case example a brine positive displacement cooling plant is assessed to be used within the mine environment. The location that would see the greatest impact, is the end of zone 2 and the beginning of zone 3 (Figure 1). This is a high traffic area, with opportunities to cool both the workforce and equipment within the operations. Using the data found in Table 1 and the same calculations used to find the energy and cost of a headframe cooling plant, the cooling plant load is determined at 1668kW and at a cost of $266,133 for 365 days a year operation.

Mix Flow Cooling

In some cases there are opportunities to mix or combine airflows to cool environmental conditions within an excavation. This can be done when there is a significant imbalance of characteristics between two airflows. In the case study there is an opportunity to bring air from Circuit C into Circuit A (Figure 1). In order to assess the new temperatures after mixing the air at different mix ratios, the new wet bulb globe temperature ($\mathrm{t_3}$) can be found by using; [1]

$$\mathrm{t_3 = t_2 + m_1(t_1 - t_2)/m_3}$$

Where;
The average summer shaft supply wet bulb globe temperature (t_1) is 23.79 C°.
The average summer brine storage supply wet bulb globe temperature (t_2) is 23.65C°.
The shaft supply air mass flow (m_1) is 57 kg/sec.
The mass flow of brine supplies air to be mixed (m_3) for a total percentage is; 111kg/s (100%), 97.5kg/s (75%), 84kg/s (50%), and 70.5kg/s (25%).

The resultant wet bulb globe temperature mixed flows are;

23.72C° at 100% mixture
23.73C° at 75% mixture
23.75C° at 50% mixture
23.77C° at 25% mixture

The mixed flows from two separate supply sources provide very little change to the environmental conditions, except for the increase in mass flow through the drift. Alternatively the mix flow enthalpy ($\mathrm{h_3}$) can also be considered to reduce the heat energy content within the air. [1]

$$\mathrm{h_3 = \frac{h_1 * m_1 + h_2 * m_2}{m_1 + m_2}}$$

The shaft supplied enthalpy of the air (h_1) is 98.6 kJ/kg.
The brine storage enthalpy of the air (h_2) is 78.81 kJ/kg.
The mass flow of the air from shaft (m_1) is 57 kg/sec.
The mass flow of brine supplies air to be mixed (m_2) for a total percentage is; 54kg/s (100%), 40.5kg/s (75%), 27kg/s (50%), and 13.5kg/s (25%).

The resultant enthalpy mix flows are

88.97 kJ/kg at 100% mixture
90.38 kJ/kg at 75% mixture
92.24 kJ/kg at 50% mixture
94.81 kJ/kg at 25% mixture

The enthalpy drop is much more significant, when compared the drop in wet bulb globe temperature under the same conditions. This is an important tool when the ventilation engineer is planning mix flows as part of changing airflow patterns for heat management. In order to do an economic assessment on the routing of air within the circuits, fan power and cost of operation must be assessed. The fan power (kW) (brake power) may be calculated;[1]

$$\text{Brake Power} = \text{Air Power} / \text{Fan Efficiency}$$

Where the fan efficiency is 65% and the air power found by;

$$\text{Air Power} = Q * H_{total}$$

Where Q (m^3/sec) is the air flow and H_{total} (kPa) is the total head pressure. This can then be applied to 365 days of continuous operation at the cost of energy, in this case 0.065$/kWh.

Table 2- Fan Operational Cost

Q (m^3/s)	Total Pressure (Pa)	Brake Power (kW)	Cost ($)
91.7 (100%)	176	25	14122
80.5 (75%)	136	17	9571
69.4 (50%)	101	11	6120
58.26 (25%)	71	6	3618

Passive Heat Removal and Recirculation Circuits

Utilizing the dry bulb temperature imbalance between the rock strata and air is an opportunity for the ventilation engineer to reduce heat stress conditions, at a relatively low implementation cost. In the case study mine, thermal conductivity heat flux plates were installed throughout the study area to observe the thermal interaction between the rock and the air. This data was critical in establishing absorption and release rates of energy (W/m²). The absorption rates observed within Zone 6 in the back of the excavation can be observed in Figure 2.

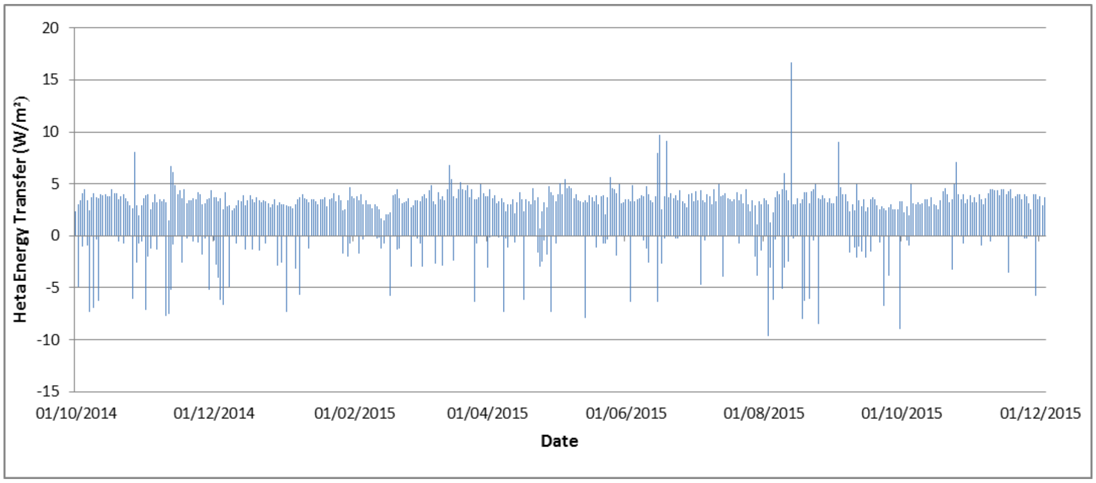

Figure 2- Zone 6 Back Heat Energy Transfer

Using the data from the heat flux plates installed in the walls and back of the excavations allows the ventilation engineer to obtain heat transfer data that can be applied to barren excavations to route or recirculate air to passively remove heat. It is important to develop an understanding of the variations in absorption rates as the heat is removed and the air temperature approaches the virgin rock temperature. This can be done by placing instrumentation in multiple locations that vary in environmental conditions due to the application of controlled air recirculation. Brake power of the fans used to route the air may then be assessed to find the cost of operation, as discussed in the previous case.

Conclusion

The ventilation engineer may be faced with a number of scenarios around heat stress and heat management. There are multiple control systems that may be implemented in order to reach the needs and goals of the mine. A strong understanding of the environmental conditions that are being faced and the circumstances that affect the conditions are critical to successfully executing heat management strategies. The operational cost of the systems that are being considered and their effectiveness is an important consideration for the ventilation engineer. Heat avoidance methods are an option; however the successful implementation of heat management control systems may boost the overall production and cost efficiency of the mine.

References

[1]De Souza, E., "Mine Ventilation Practitioners Guide", 2011

[2]https://energydesignresources.com/media/1681/edr_designbriefs_chillerplant.pdf?tracked=true