Diurnal Thermal Flywheel Influence on Ventilation Temperatures in Large Underground Mines

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The daily temperature variance between daytime and night-time can have a significant influence on the ventilation conditions within a mine. Air temperature variations are reduced as air travels further into a mine due to the storage and release of heat in rock boundaries and variations in heat transfer between rock and air. Heat modelling has traditionally focused on utilizing maximum daytime temperatures to predict limiting underground condition; however, the minimum night-time temperatures may have significant influence on overall mine temperatures.
A study was undertaken to measure temperature at locations throughout a large mine continuously over a week to identify and quantify the thermal flywheel behavior. This paper presents the findings and conclusions of the study and demonstrates that limiting temperatures predictions can be improved by considering diurnal temperature changes.

SECTION 1: INTRODUCTION

The thermal flywheel effect as applied to mine ventilation can be defined as the absorption and release heat from a rock mass exposed to differing ventilation temperature cycles. [1] This effect provides a thermal 'inertia' against temperature fluctuations and stems back to the mechanical use of a rotating mass commonly used to gather energy from fluctuating input sources and release energy in a more continuous and consistent manner. [2]

Storage and release of heat from a ventilated rock mass can take place during any cyclical air temperature event such as changes in heat producing activities during a work shift (diesel machinery movements for example), a day and night surface temperature cycle, or a seasonal cycle over summer and winter. As air moves through a tunnel system, the absorption and release of heat from air temperature cycles reduces and 'dampens' the temperature cycle, becoming less pronounced the further the air moves into the ventilation circuit.

A definition problem with the term 'thermal flywheel' as applied to mine ventilation is that it implies energy is both stored and released from the rock. Depending on the age of exposure of the rock and whether the rock is consistently warmer or cooler than the air temperature cycle, it is possible that transfer of heat may only occur in one direction. While the rate of heat transfer will still be cyclical with differing rock and air temperature changes, the total heat flow will be unidirectional which is inconsistent with the storage and release definition of 'flywheel'. However, the effect still results in a damping of temperature variations, thus a more accurate description may be the "Thermal Damping" or "Thermal Buffer" effect.

Experimental Analysis of the Daily Temperature Cycle.

Modelling and predication of underground temperatures has traditionally been performed using steady state analysis of a single temperature. Typically, this is a peak daytime surface temperature representing an upper expected temperature likely to be experienced at a mine. Given that this only represents a small part of the daily temperature cycle however, the likely range of temperatures over 24 hours is not calculated, and an analysis was performed on an operating mine to test the effect of the daily temperature variances on underground mine temperatures at different locations.

Anecdotally, it is well known that the flywheel effect significantly dampens out temperature variations the further the air travels into the mine. In this study, the goal was to:

- Measure the temperature variance on surface and through different locations through the mine over the course of a week.
- Analyze how quickly the dampening effect occurred based on distance and length of time into the mine.
- Observe thermal flywheel storage and release of heat effects, versus cycling variances in rock heat release.
- Propose a method of predicting the variance of temperatures at different location
- Comment on the validity of single steady state temperature prediction versus transient flywheel temperature prediction.

SECTION 2: CASE STUDY

The research study was performed at Ernest Henry Mine in North Western Queensland, Australia. Ernest Henry Mine is a sub-level cave copper and gold mine owned by Glencore and extends over 1.0km deep with a total ventilating airflow of over 850 m^3/s. The mine is located north of the Tropic of Capricorn resulting in hot summers, and mild dry winters. The study was performed during the winter period where ambient surface temperatures ranged from a minimum 10^0C at night to a maximum 30^0C during the day.

Thermal inputs to the mine are consistent with most modern mechanized mines with mine heat inputs from rock strata, autocompression, diesel machines and electrical infrastructure. Final extraction of ore and waste is by hoisting shaft, with only limited diesel truck activity through the mine. The mine has relatively high rock and geothermal gradient temperatures, and is cooled with refrigeration during the summer months.

Methodology

The relatively low diesel heat input in the tested regions assisted in isolating the diurnal thermal flywheel effect from other heat cycles such as equipment activities, however there was still significant 'noise' from mining activities which influenced temperatures at times. A total of eight (8) temperature and humidity logging devices were placed through the mine and on the surface to cover a wide range of distances from the surface intake air (Figure 9). The devices were relatively cheap temperature loggers (Figure 1) with temperature accuracies of only 0.5^0C however all showed nearly identical ($<0.5^0$C) temperatures before being placed giving confidence that accurate results would be obtained. As the devices only measured ambient temperature and humidity, the following formula was used to estimate wet bulb temperatures to within 0.1^0C accuracy. [3]

$$T_w = T\,\mathrm{atan}[0.151\,977(\mathrm{RH\%} + 8.313\,659)^{1/2}] + \mathrm{atan}(T + \mathrm{RH\%}) - \mathrm{atan}(\mathrm{RH\%} - 1.676\,331) + 0.003\,918\,38(\mathrm{RH\%})^{3/2}\,\mathrm{atan}(0.023\,101\mathrm{RH\%}) - 4.686\,035.$$

Equation 1

Figure 1: Digitech Datalogger Model XC0424

The devices were left in place for seven (7) days and logged data every one (1) minute collecting over 10,000 samples each. To reduce the chance of damage or loss, the devices were placed where possible in protected cuddies or indentations in the rock walls. At the end of the period, the monitors were recovered and returned to the surface where the data downloaded.

Observations

Figure 2 shows the daily cyclical surface temperature variations over the study. During the week, due to increasingly warmer weather, the daily maximum temperatures increased from 22^{0}C to 30^{0}C. Maximum wet bulb temperatures increased from 12^{0}C to 16^{0}C through the week. Diurnal variations between high and low temperatures were typically around 12^{0}C dry bulb and 6^{0}C wet bulb throughout the period.

The temperature profile shows a maximum temperature at around 3:00pm and a minimum temperature at 5:00am, just before dawn. The transition of temperatures from night to day is relatively sharp, while temperature reduction after peek day time temperatures tails off more slowly.

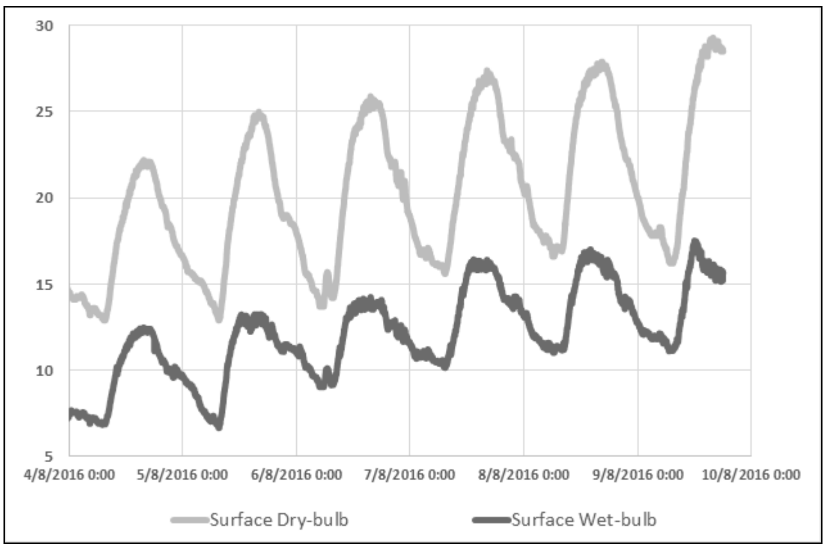

Figure 2: Surface Daily Temperature Variations Wet and Dry Bulb (degrees C)

Figure 3 shows the variance of heat flow added in the mine during day and night cycles, and excludes the heat added by the main exhaust fans. The heat added to the airflow in and out of the mine can be estimated by calculating the Sigma Heat content of the air using Equation 1 and 2, adjusting for elevation difference (equation 4) and then multiplying the difference in exhaust and intake heat content by the mass flow (estimated at 1050 kg/s) of airflow through the mine using equation 5.

$$S = \frac{0.622\, e_{sw}}{(P - e_{sw})}(2502.5 - 2.386\, t_w) + 1.005\, t_w \qquad \frac{kJ}{kg}$$

Equation 2

Where saturated vapour pressure is defined as

$$e_{sw} = 0.6106 \ \exp\left\{\frac{17.27\, t_w}{237.3 + t_w}\right\} \qquad kPa$$

Equation 3

The elevation enthalpy adjustment is

H_e = g x ▲H /1000 Equation 4

Where g = gravitational constant (9.81 m/s^2), and

▲H = difference in height (m) between intake and exhaust

Heat Flow Added (MW) = massflow x (S_{out} – $S_{in + H}$) / 1000 Equation 5

The heat flow cycles are opposite the surface temperature cycles and vary by nearly 20MW, indicating the huge effect of intake temperature on heat draw from the mine rock mass. In fact, the diurnal change in temperature and resultant heat flow far outweighs the estimated mechanical heat input into the mine of approximately 6MW.

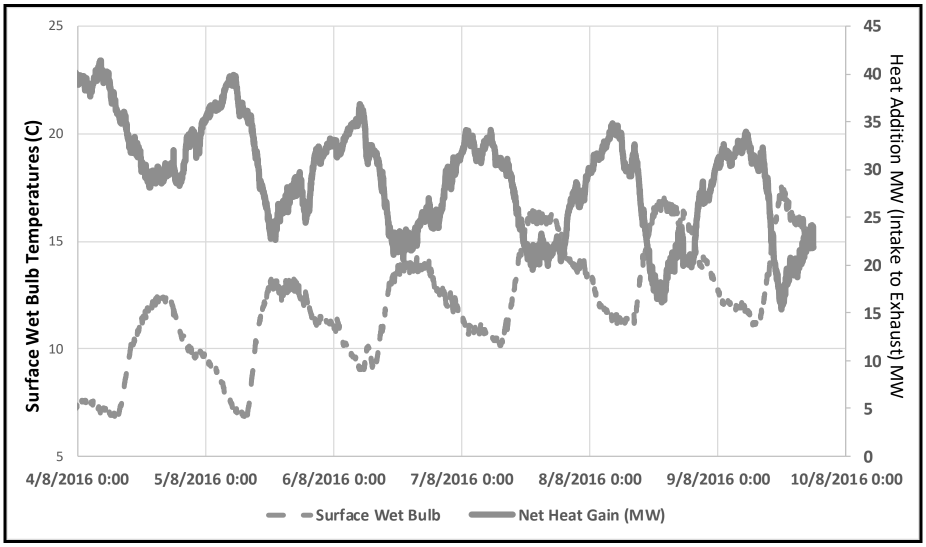

Figure 3: Heat Flow (MW) added between Intake and Exhaust vs Surface Wet Bulb Temperature

Figure 4 and Figure 5 shows the differences between two of the upper monitor locations versus surface temperatures. Despite being a similar distance from the surface intake, the shaft location shows a higher range of variation due to higher air velocities and less time for the air to reach the location. Despite the air temperature strongly influencing the heat flow from the rock, the graph fails to show lagging temperature cycles indicating the thermal flywheel rock boundary storage and release effect is relatively insignificant.

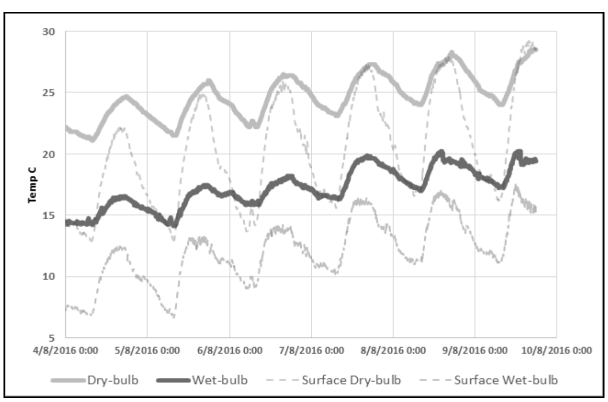

Figure 4: Wet bulb temperature variances at the base of the Hoisting Shaft (900m from surface)

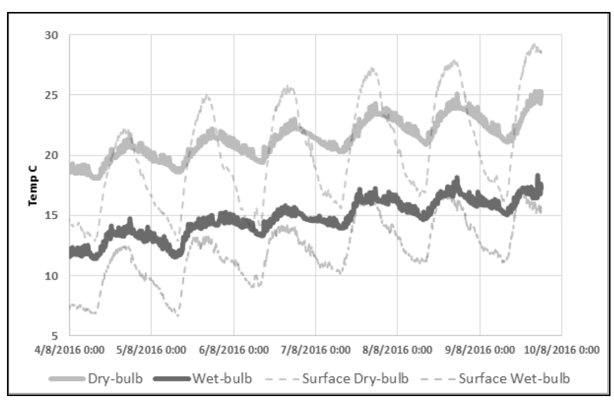

Figure 5: Wet bulb temperature variances on the Main Decline (1000m from surface)

Figure 6 shows only a slight correlation between surface temperatures and underground locations at a position 3500m from the surface. Figure 7, at the exhaust fans approximately 4400m from the surface entry shows the correlation is insignificant, and mostly overwhelmed by scattered heat 'noise' from mining activities.

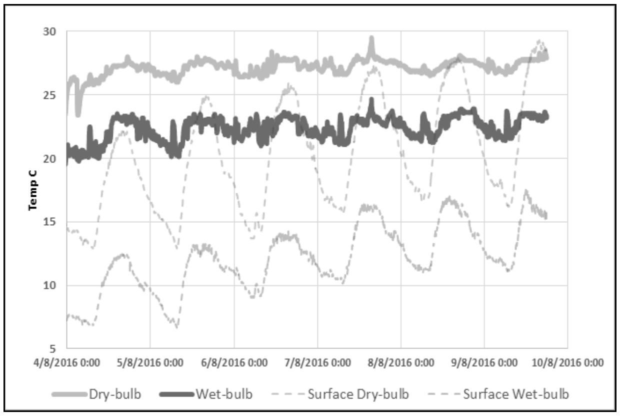

Figure 6: Temperature variance on the main ramp (3500m from surface)

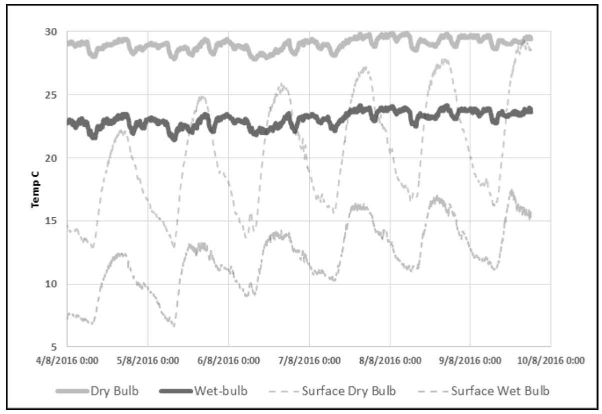

Figure 7: Temperature variance at the exhaust shaft (4400m from surface)

SECTION 3: THEORY OF ROCK HEAT TRANSFER

Prediction of rock heat transfer to and from ventilating air in a tunnel network is not trivial. Upstream results directly impact downstream calculations, and the process requires a ventilation system be broken into discrete small increments where a cascading flow algorithm can be applied through the model. [4] In the event of recirculating air, the process must become iterative to converge to a steady state solution. Heat transfer from rock to air is largely dependent on the difference in temperature between the two elements, but is also strongly dependent on other factors such as;

- Rock properties and wetness
- Virgin rock temperature and age of exposure of the rock to air
- Velocity of air
- Size and shape of the airway

Ventilation modelling and heat prediction from rock strata at discrete locations has typically been performed using radial heat transfer methods. The methods allow the prediction of heat transfer across a plane section from boundary rock surfaces to air, based on the properties mentioned above. A key component in the calculation is estimating the temperature gradient at the exposed rock surface. Before the availability of more powerful computers, this was done using numerical integration techniques, the mathematical methods which are described here. [5] The methods were originally used to establish calculation tables in books, which were used to assist in calculations of heat transfer from rock strata. Gibson [6] published an algorithm which could computationally replace the complex numerical integration methods of the Carslaw and Jaeger solution to within 2% error accuracy. The methods are presented clearly in McPhersons book "Subsurface Ventilation Engineering". [1]

Network Modelling

The calculation of thermal heat transfer at one location is not generally useful for mine ventilation system analysis. The result of the single point will cascade and influence all downstream points in a ventilation system, and this is further compounded by mixing airflows of differing temperature and humidity from different locations. Thus, a network solver is required to iterate through a model and take the upstream heat inputs and cascade the results into downstream areas all the way through to an exhaust exit. Commonly used modern solvers for thermodynamic analysis include Ventsim™, Climsim™, Vuma™ and Multiflux™. [7] [8] [9] [10]

Limitations of Steady State Analysis

When rock is initially exposed to air, heat transfer from temperature differences is rapid, however over time transfer between rock and air lessens as they become closer in temperature. A flaw in utilizing classical radial heat transfer methods for practical applications is that it assumes steady state conditions in temperature and does not store or consider any history of temperature changes. If the simulated air temperature is significantly outside of the mean, it will incorrectly age the rock mass temperature and temperature gradient, resulting in less accurate radial heat flow.[11] Any type of temperature cycle means that the system is not steady state therefore when using radial heat transfer methods for steady state heat analysis of temperature cycling systems, compromises must be made.

- Option 1: Use peak air temperatures as a steady state model input to predict peak temperature radial strata heat and downstream air temperatures. This method however limits assumed heat flow from the rock over time and incorrectly ages the long-term temperature of the rock mass resulting in an underestimation of heat flow and hence an over estimation of temperature at peak times.
- Option 2: Use a long-term average air temperature to model the average radial heat and predicted temperatures. While this is more accurate for predicting average rock heat transfer over time, it under predicts peak air temperatures in the mine (particularly in upper areas) which often form the critical part of the analysis of heat in mines.
- Option 3: Combine a transient analysis of the above methods to account for the deficiencies of either method alone. [12]
- Option 4: Consider an alternative network method such as Numerical Transport Code Functionalization that builds matrix models of history of temperatures changes to calculate heat transfer. [13]

Option 3 and 4 apply quasi-transient methods to traditional steady state analysis. While they will provide more accurate results, they are mathematically more complex, require greater data input to establish the cyclical conditions, and require additional computational time to pre-calculate the conditions and model the network. Thus, despite the flaws presented using solely steady state methods, the steady state methods are still commonly used in many simulation tools to model rock strata heat transfer and air temperature for mine thermal analysis.

A Transient Method of Estimating Diurnal Temperature Ranges

To overcome limitations of steady state radial heat analysis, the study will analyze a transient method to improve estimation of the flywheel effect (as described by Option 3 listed above). The proposed method is a simplified version of the transient heat flow method developed for the VentFIRE™ fire simulation module in Ventsim™. [14] Roy and Singh proposed a similar transient based solution that iteratively passed air and rock temperature solutions from the initial steady state solution into subsequent calculations of the succeeding time span, however this solution was only tested against theoretical calculated values in a single airway, not against a large ventilation network. [12]

In this study, only the diurnal variation is being considered, hence the analyzed conditions are only the high and low daily temperatures. Short term equipment heat changes and long term seasonal changes are ignored.

- For the steady state base case, the high and low temperatures were input into conventional steady state radial heat network simulation and simulated at approximately the rock exposure age.
- For the transient method, a mean temperature at the rock exposure age is used to establish the conditions of the rock mass and the rock boundary temperature results of this calculation are then used as base conditions for establishing the short-term heat transfer (12 hours) between day and night extreme conditions. Ventsim Visual was modified to include the three-pass quasi-transient method to provide a comparison to measured results and steady state results. The method is called as 'quasi' as it does not entirely embrace full transient methods of energy balance over time, but rather combines multiple steady state solutions.

SECTION 4: SIMULATION RESULTS

The proposed transient method was applied to the case study data to analyze the effectiveness and accuracy of the approach. The results are shown in Figure 8 and Figure 9 which compares temperature variances between day and night against distance from the surface air intakes. The graph shows a comparison between measured results, results obtained using steady state day and night temperatures analysis, and results using the three-pass pseudo transient method described above. The three-pass transient method provides a much closer estimation of temperature variance between day and night temperatures, which assists in more accurately predicting conditions likely to be experienced over a 24-hour period at any location in the mine.

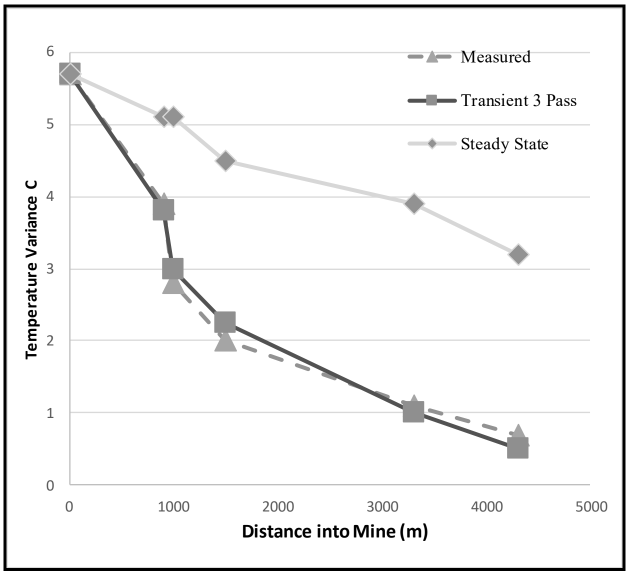

Figure 8: Wet bulb temperature variance between day and night vs distance from surface

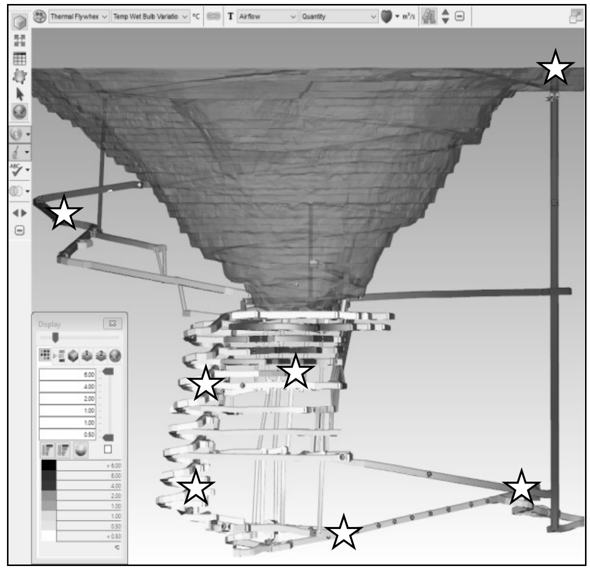

Figure 9: Ventsim Visual model with darker colors showing higher day/night wet bulb temperature variance. Monitor locations are shown as ☆

The model tested was not calibrated to all mine heat producing activities at the time and therefore is not considered a precise heat model and the results should be taken cautiously. The measured temperatures versus simulated temperatures for day and night time are shown in Figure 10 and Figure 11. The steady state day time temperature analysis performed well (due in part to the intake air temperature being closer to the rock temperature), and was similar in most cases to the transient temperature estimates. The night time temperature performed poorly using steady state methods, underestimating wet bulb by an average of nearly 2.5^{0}C in the further sections, while the transient method performed more closely, overestimating temperature by approximately 0.7^{0}C for the same region.

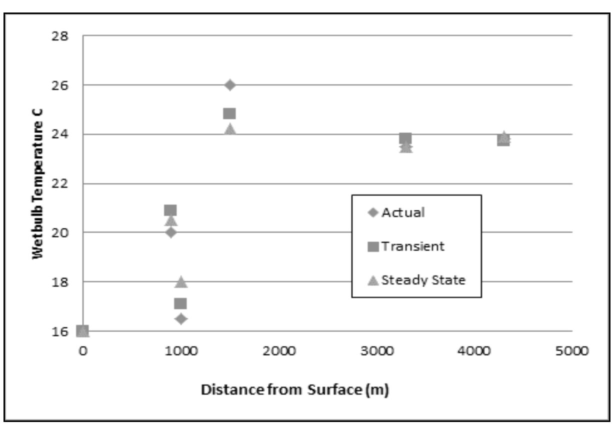

Figure 10: Daytime Modelled Wet Bulb Temperature Results

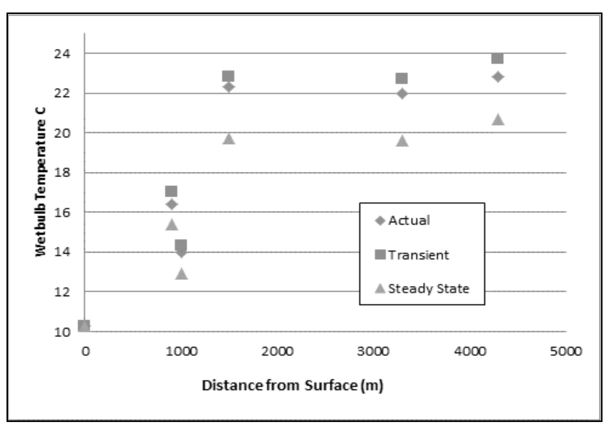

Figure 11: Nighttime Modelled Wet Bulb Temperature Results

Conclusions

Significant damping of temperature variances occurred throughout the mine, reducing day and night differences by approximately 40% every 1000m of travel from the surface. The damping amount however is not determined entirely by distance from surface, but also varies with air velocity, rock thermal properties and the magnitude of temperature variation from air to rock.

The 'flywheel' effect as pertaining to the definition of storage and release of heat was not observed. Heat flow from rock to air throughout the temperature cycle remained one-way. In this case, the rock was consistently warmer than the air in most places, and this resulted in cyclic heat outflow from the rock at amounts inversely proportional to the local air temperature.

Applying steady state radial transfer methods to air temperature cycles produces poor results. Using maximum surface temperatures to calculate limiting mine temperatures is also risky as it poorly conditions the long-term rock age parameters, and ignores the thermal damping effect. In summary, it will tend to over-predict high temperatures and under-predict low temperatures. In this study, the high temperature prediction was still reasonably accurate (at the expense of low temperature prediction), but this may not be the case in a mine with different rock and surface temperature parameters

Applying the simplified quasi-transient simulation method to incorporate the thermal damping effect gives more accurate results for both the upper limiting temperature and temperature variances over the 24-hour temperature cycle compared to steady state methods. This effect becomes more pronounced when there is a significant difference in air and rock temperature.

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