ESTIMATING THE SEASONAL PERFORMANCE OF A SURFACE REFRIGERATION COOLING PLANT FOR AN UNDERGROUND MINE

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ABSTRACT

Tunnel ventilation and mine ventilation overlap in several areas. One key area is in the analysis of heat and how this can affect processes and people. A range of ventilation and thermal models have developed in parallel to support both industries, with occasional cross-industry use. In this paper we describe the cross-industry use of a mine ventilation model with a transient thermal tunnel ventilation model that WSP developed. The paper describes how the models were used together to answer important questions that could not readily be answered by one of the models alone.

The notional mine used for the case study would have experienced hot conditions at the working faces. A cooling plant at the surface was analyzed as they can be cost effective compared to an underground cooling plant. However, with the working faces a long way from the plant the cooling effect can be compromised by the time the air gets to where it is needed. The accurate evaluation of heat transfer between the rocks and the ventilation air, including seasonal impacts, is therefore important.

Tunnel ventilation models have good capability to model strata heat transfer and can be used in conjunction with the mine ventilation models to understand system performance. In this paper we also report on the performance of a surface cooling plant accounting for such heat transfer from the ground and go on to describe how the position to the cooling plant relative to the surface can have an important impact on how effective the cooling can be.

Keywords: Mine Ventilation, Tunnel Ventilation, Seasonal Performance, SES, Dynamo, Heat transfer

1. INTRODUCTION

Mine and tunnel ventilation analysis and engineering are similar. Both requiring a good understanding of fluid dynamics, network modelling and heat transfer as well as a practical understanding of fan engineering, cooling, flow measurement and flow control. There are, however, several important differences between the two that affect the nature of the modelling tools and approaches they use.

An excellent background into mine ventilation can be found in McPherson’s Subsurface Ventilation Engineering [1]. Mines are normally significantly deeper than tunnels and with this comes the need to account for the compressibility of the air at depth which results in a heat input to the air. Just as air cools as altitude increases, it also warms with depth which in the mining industry is referred to as auto-compression. Without other heat transfer this results in approximately 1°C of warming of the air per 100m depth increase, regardless of the air flow rate. Other important differences relate to the complexity of the networks, with many local flow branches and divisions in mines. A considerable amount of practical experience and domain knowledge is needed for mine ventilation to understand the likely hydraulic resistance of different types of mine walls, conveyances, and stoppings/seals; heat emissions from the ore and processes like blasting; engine emissions for mine vehicles and the control of gases emitted from the strata. Control of gasses and dust contaminants such as silica and diesel particulate matter can also be a consideration. The difference in density and mass between two vertical columns of air will generate a pressure differential that needs to be considered in underground mines, such effect is named the natural ventilation pressure and may have a great impact on the fan selection. The difference in density is a result of geothermal heat as well as heat output of underground machinery.

An excellent background into tunnel ventilation engineering can be found in the Subway Environmental Design Handbook [2]. Road, rail and utility tunnels tend to be shallower than mines and hence factors such as flow compressibility and auto compression can normally be ignored. A good deal of practical experience and domain knowledge is needed for tunnel ventilation to understand rolling stock traction movement, piston effects and heat emissions; pressure comfort; management of air speeds in public areas; transient thermal comfort; fire engineering and practical combined control of multiple ventilation plants, dampers, and systems.

Both mine and tunnel ventilation typically require the use of network modelling. Given the previously mentioned differences, not surprisingly differences emerge in the software used. At WSP we, and the specialists that support us on some projects, have tended to use Howden’s VentSim™ for mine ventilation analysis [3]. It is widely used in the mining industry with a good user and support base. It has strong graphics capability, is tailored for the mining industry with pre-populated information and templates specific to mining and, importantly, includes for compressible variable density flow and auto-compression heating. The thermal model for the strata heat transfer is well validated but relies on the application of a semi empirical method to approximate the impact of cyclic and seasonal heat transfer into the ground. Other mine ventilation packages we understand to use a similar approach.

For tunnel ventilation we predominantly use the Subway Environment Simulation (SES) software which we co-developed (in the guise of Parsons Brinkerhoff) and continue to support and update [4]. The programme is well validated, with strong confidence in its aerodynamics results. Thermodynamically, the programme is well validated and, for example, WSP and London Underground [5][6] have used it to model each of the lines on the Underground and found it capable of predicting summer temperatures very well compared to a great deal of temperature validation data that was available on the project. Whilst we have confidence in the software, like VentSim™, it also relies on a semi empirical analytical method to calculate the wall heat transfer. This simplification is usually sufficient, but when there is a need to understand in better detail transient effects such as nighttime cooling and seasonal cooling WSP developed a companion package called Dynamo to model such thermal transient events. The tool was developed for modelling tunnel systems and can manage transient behavior in all inputs to the model.

Dynamo is a flexible energy balance model with a finite difference-based heat sink that can predict in tunnel environments. The tunnel is broken down into segments (normally around 200m long) and for each segment the ground is model as a radial set of finite elements nodes and rings. Inlet conditions are passed through the various segments and heat gains and latent heat transfer can be represented, along with such features as cooling pipes, ventilation shafts and embedded cooling pipes within the tunnel wall. With the right choice of nodal spacing the software was validated to within 0.1K by comparing the predictions of a matching case to an exact analytic solution of the transient cycling heat transfer equations [7][8]. Dynamo can provide transient analysis with continually varying scheduled inputs and outputs. It has been used to model several unorthodox heat transfers in tunnels, including heat waves [9] and tunnel heat recovery [10]. Flow boundary conditions are input into the software from the 1D network models. Fourier number re-scaling is used to initialize the model and reduce simulation time and thereafter a typical 50-segment model may take around one hour to run on a laptop PC.

2. CASE STUDY – SOFT ROCK UNDERGROUND MINE

Model inputs

For this case study we considered an underground mine in a continental climate. An outside weather file climate was synthesized with an average temperature of 14.7°C and a 1% exceedance temperature of 35.8°C.

The mine was modelled as 750m below ground and with a virgin rock temperature of 40°C at depth. The working faces extended 5 km from the main intake shaft. A single ventilation station was included in the model located below ground 1km into the mine. This ventilation station delivered 125 m³/s of outside air that was shared between the working faces. Inevitably some of that air was modelled as lost due to leakage into the return air gallery at crosscuts mainly for vehicle crossing. The fans positioned on the intake added an additional 800 kW into the air due to compression and inefficiencies. The mine was modelled as a constant 6m by 5m cross-section. The ventilation flow was assumed to branch off after 4 km into the mine to serve working faces. For a given working face, a flow rate of 25 m^3/s was assumed. A schematic of the mine ventilation system is shown in Figure 2.

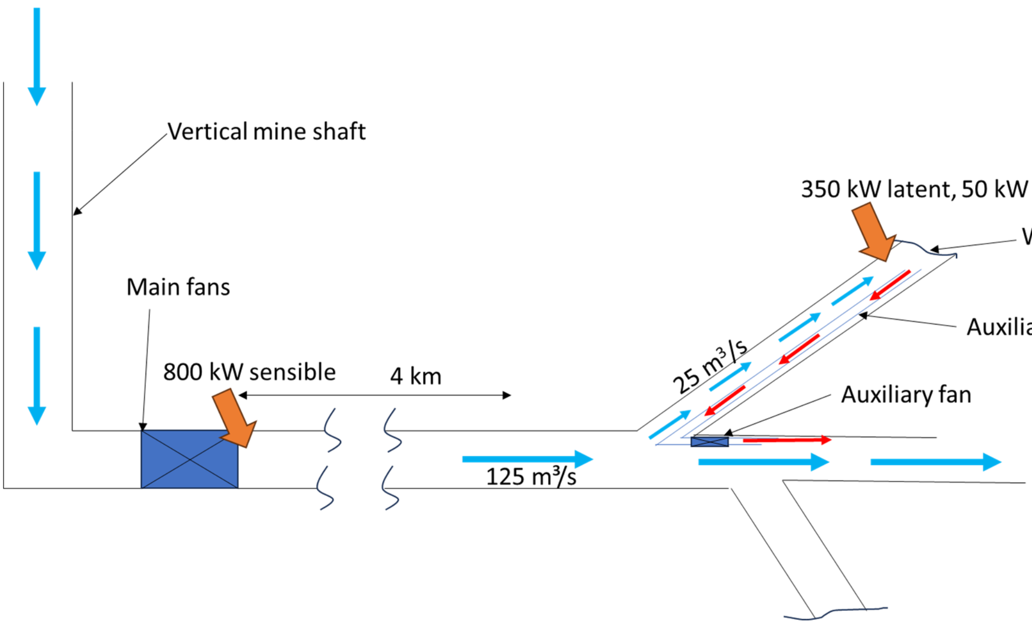

Figure 1: Schematic of test case mine

Each working face was assumed to use an electrically powered continuous panel miner with one to two 25-tonne diesel trucks removing the mined mineral and discharging it into a conveyor in the return air gallery. The working galleries can be up to 350m long and are ventilated with an exhaust auxiliary fan and flexible duct arrangement. The fresh air is supplied and exhausted from the main ventilation gallery and then passed into the return air drift. The fragmentation of the rock by the continuous miner can generate a lot of dust. Water spraying is used both cooling the panel miner and then onwards for dust suppression. Based on our measurements from other mines, the mining process for such mining method with similar sized equipment is estimated to result in an average of 350 kW latent heat emissions and 50 kW sensible heat emissions. Much of the latent heat emission is caused by direct and then later re-evaporation of the dust suppression water, as well as latent heat from the truck emissions. A working face schematic and the types of equipment can be seen in Figure 2.

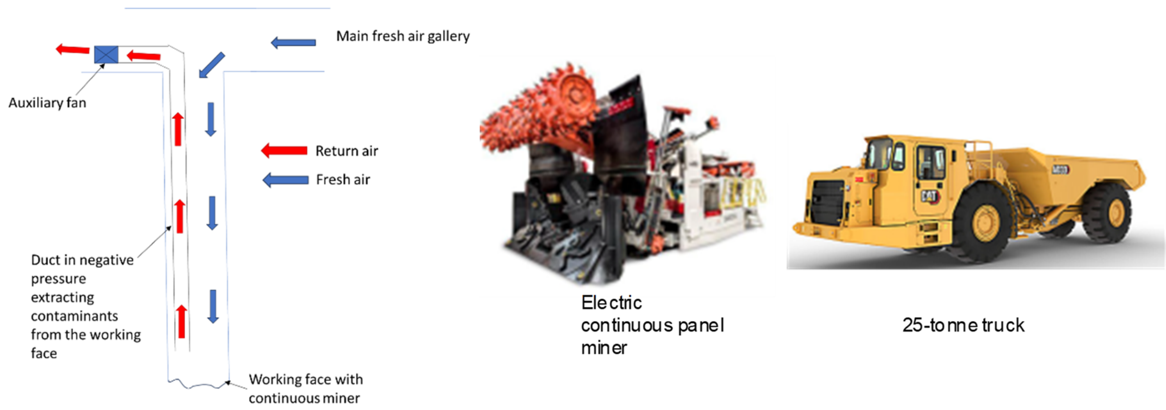

Figure 2: Mine face process

Cooling options

The starting point in managing mine conditions should be maximizing the capacity and effectiveness of the local ventilation at the working face. In practice, this can be challenging, particularly in cases where pillar mining cannot be used, and sinuous drives are used to reach the face. This is due to duct size being limited by the space used by the truck. For this case study the local exhaust capacity was set to a limit of 25 m^3/s. To increase this capacity at the working faces the main fans must have enough capacity to provide this airflow at the face while minimizing leakage in crosscuts. If they don't a tradeoff analysis must be conducted to evaluate if it is more feasible to increase the capacity of main fans or install a mechanical refrigeration plant. Mine cooling from the surface is normally more practical for installation and heat rejection purposes. Some or all the intake air is cooled and introduced at, for example, 12°C rather than 30 to 35°C in summer. The cooling will also lower the humidity ratio of the outside air. This method has the major drawback that the cooled air will collect heat from the strata on the way to the working face and become warmed. The alternative is to provide cooling within the mine using air handling units located in excavated side-streams. This limits the heat transfer from the strata but has the cost of installing and maintaining the equipment underground and the challenges to reject the heat in the hot and humid return air stream.

For this study we considered some of the differences between surface and below ground cooling using a case study and a combination of VentSim for airflow and heat generated from the working face and Dynamo for transient heat transfer with strata. The case study was developed to answer the following questions:

1. What is the impact over time of the cooling of air on the strata heat transfer?
2. What is the seasonal performance of the cooling considering the thermal flywheel effect of the ground (the rate at which heat energy is absorbed and released by the surrounding strata during the daily and annual temperature fluctuations)?
3. What peak capacity in-mine plant may have the same effect as a surface plant?

Model results

The results are compared against thermal safety indices. Different countries and mines have different indices that they use to manage worker thermal safety. For this study we report wet bulb globe temperature (WBGT) [11] and Effective Temperature (ET). WBGT can be calculated as the sum of 70% of the air wet-bulb temperature and 30% of the air dry-bulb temperature (in degrees C). ET can be complex to calculate, but in mining applications can be simplified as the sum of 90% of the air wet-bulb temperature and 10% of the air dry-bulb temperature. Again, different mines and countries set different limits on WBGT or ET. For this application we consider acclimatized workers and eight-hour shifts at the working face with an ET limit of 31°C.

Figure 3 in Appendix 1 shows the results of the base case (i.e no mechanical cooling and ventilation only). The mine was predicted to stabilize thermally after three or four years, a prediction that could not have been ascertained from a mine ventilation model alone. The annual temperature variation at the bottom of the air intake shaft was around 11K dry bulb, less than outside because the shaft moderated the outside air temperature fluctuations of close to 35K. The11K annual swing in temperatures at the base of the shaft reduced to only 4K at the face. This was as a direct result of the air to wall heat exchange as it passed along the warm mine walls on its way to the working face. Once at the face the daily variation in dry bulb temperature was predicted to be small. There was a higher fluctuation in wet bulb temperature since the strata did not act to buffer the changes in humidity ratio of the air prior to it reaching the face. The WBGT and ET were predicted to be quite stable in summer, with conditions of between 35 and 31°C respectively. The daily range can again be mostly attributed to the changes in humidity ratio rather than dry bulb temperature.

Figure 4 in Appendix 1 shows the impact of 5 MW of surface level cooling with a dew point temperature of 10°C on the coil and a contact factor of 0.9. The system was predicted to be operating at thermal maturity within a year. This was because the strata heat transfer negated most of the sensible cooling effect prior to the air reaching the working face. The system was predicted to reduce the maximum ET by 5K and the average ET by 1.9K. This compares with 4.8K and 2.0K for maximum and average WBGT respectively. The difference in these two metrics can be considered marginal.

Most of this improvement in thermal safety was because of the reduction in wet bulb temperature caused by the coil's dehumidification in summer. Most of the sensible cooling effect was offset by heat transfer from the ground along the length of the mine. An average air temperature increase of over 30K was observed from the cooled supply air to the working face. At the working face the summer dry bulb and wet bulb temperatures were reduced, but the winter temperatures changed little since in that condition the air on-coil conditions were typically close to or cooler than the dew point which resulted in no humidity condensation.

Figure 5 in Appendix 1 shows the impact of 2.5 MW of mine cooling, again with a dew point temperature of 10°C at the coil and a contact factor of 0.9. The contact factor of a coil is defined as the efficiency for dehumidification. In practice it is defined as the ratio between the moisture reduction achieved by the coil and the moisture reduction that would be achieved if the cooling coil could reduce the air to the dewpoint temperature of the coil. The capacity of 2.5 MW was arrived at by iteration until the summer maximum WBGT and ET were like that of the 5 MW surface cooling plant. One immediate conclusion is that a plant within the mine was capable of being only half the capacity of a surface plant for a similar summer peak impact. It is also noteworthy that the underground plant provided a much greater reduction of both dry bulb and wet bulb temperature, and a much greater variation and improvement in WBGT and ET across the whole year (rather than just in summer). This improvement in annual average conditions may be of value in improving worker safety and productivity.

Table 1 shows a summary table of the key results, including the annual average cooling capacity delivered by the plant and the summation of the annual cooling energy delivered by the cooling plant. Whilst the underground plant is lower capacity, annually it delivers more cooling, or in simpler terms, it is more heavily utilized. This is mainly because the impacts of auto compression heating and fan station warming mean that the on-coil temperature is higher. This could either be seen as a positive in that the investment in the cooling plant is more intensively being capitalized upon, or a negative in that the cooling plant is using more energy. Depending on the value of cooler conditions year-round to the cost of energy, the deep mine plant may be reduced in cooling output in winter and spring.

Table 1: Results comparison for the three cases considered

Case	No Cooling	5 MW Surface Cooling	2.5 MW UG in Mine Cooling
Max / Average Dry bulb (°C)	45.7 / 43.5	41.5 / 40.9	36.5 / 32.6
Max / Average Wet bulb (°C)	31.1 / 29.8	26 / 23.6	27 / 21.7
Max / Average WBGT (°C)	35.4 / 30.8	30.6 / 28.8	29.8 / 24.9
Max / Average ET (°C)	32.5 / 27.2	27.5 / 25.3	27.9 / 22.8
Average cooling (MW)	-	1,200	2,499
Annual cooling (GWh)	-	10,511	21,892

3. CONCLUSION

Mine ventilation models and tunnel ventilation models can be used in combination to deliver more useful results to help guide investment and performance conditions around cooling plant. They allow the seasonal performance of the plant to be appreciated and accounted.

The sensible cooling performance of surface plant can be significantly diminished by the impact of heat gains along the mine walls from the airways before the working faces. The main performance benefits can be in reducing the moisture content of the incoming air. Surface cooling plant is also best suited for reducing peak conditions in summer since in cooler seasons the cooling coils may not deliver significant amounts of cooling.

Whilst cooling plant located within the mine may be more expensive and complex to install, they can potentially be much lower in capacity to deliver a similar cooling effect. They are also able to deliver better annual changes in both tunnel air dry bulb and wet bulb temperatures compared to surface cooling plant. The plant is likely to be more highly utilized (and thus use more energy). This may either be welcome or unwelcome, depending on the mine's view on the value of cooler conditions year-round compared to the cost of running the cooling plant.

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5. APPENDIX 1 – RESULTS GRAPHS

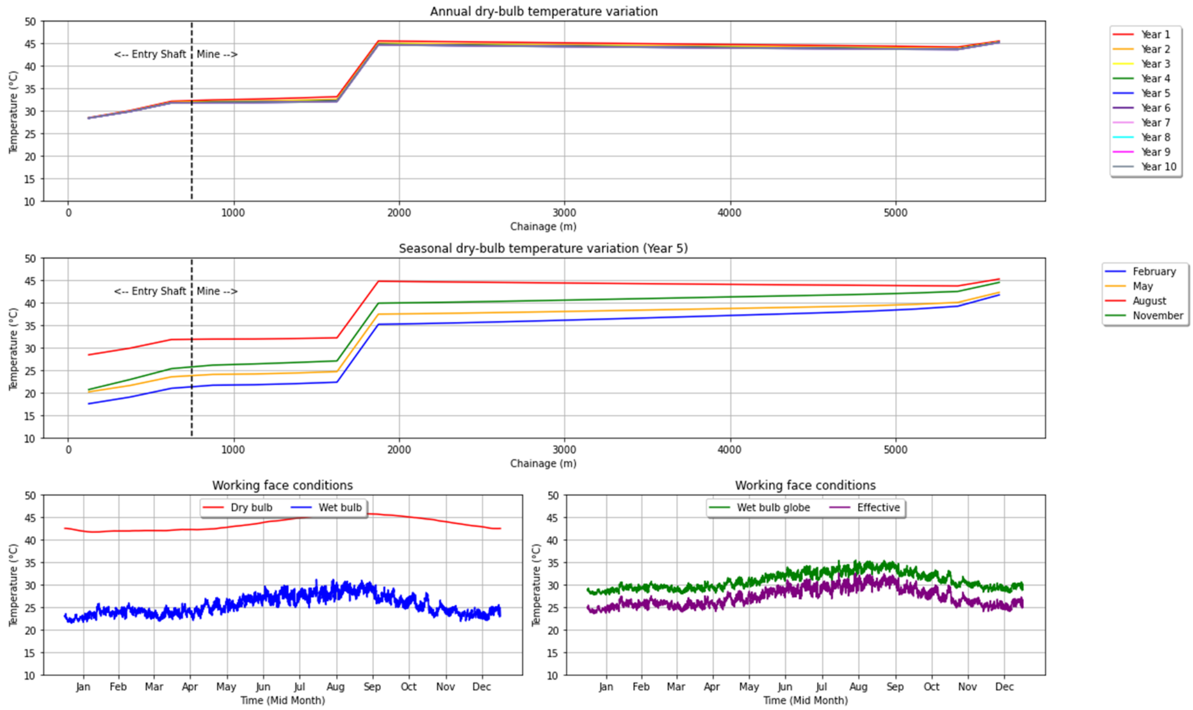

Figure 3: Base case temperature results

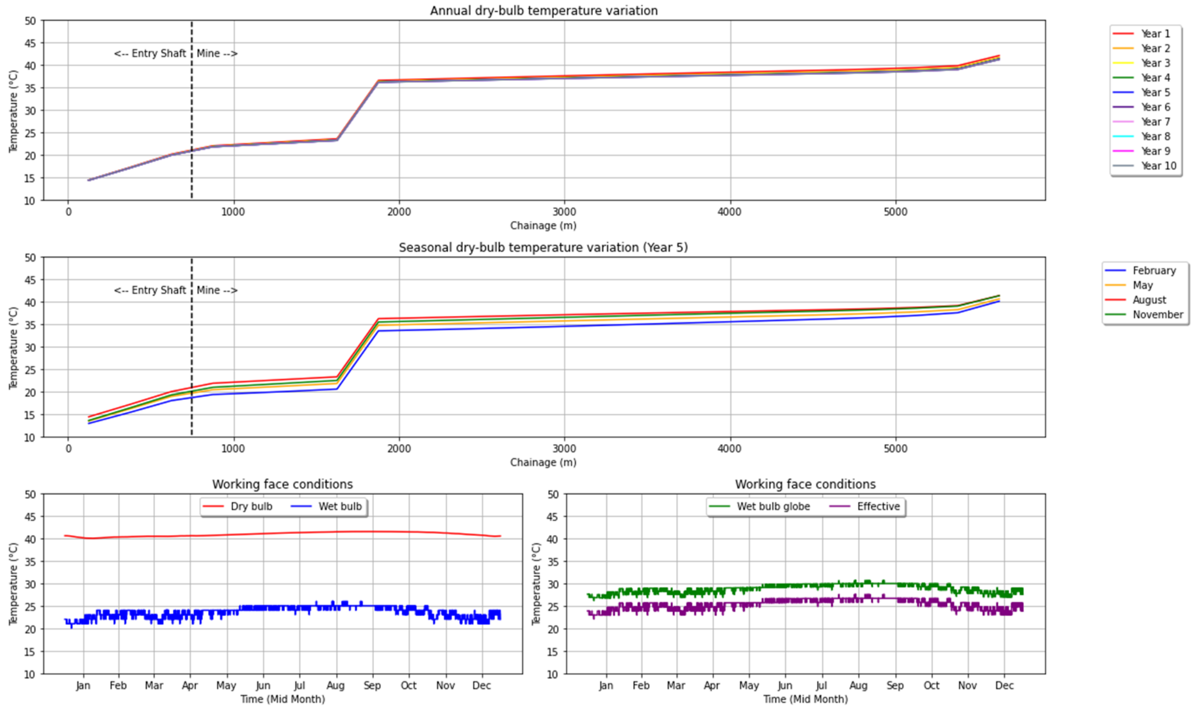

Figure 4: 5 MW Surface cooling temperature results

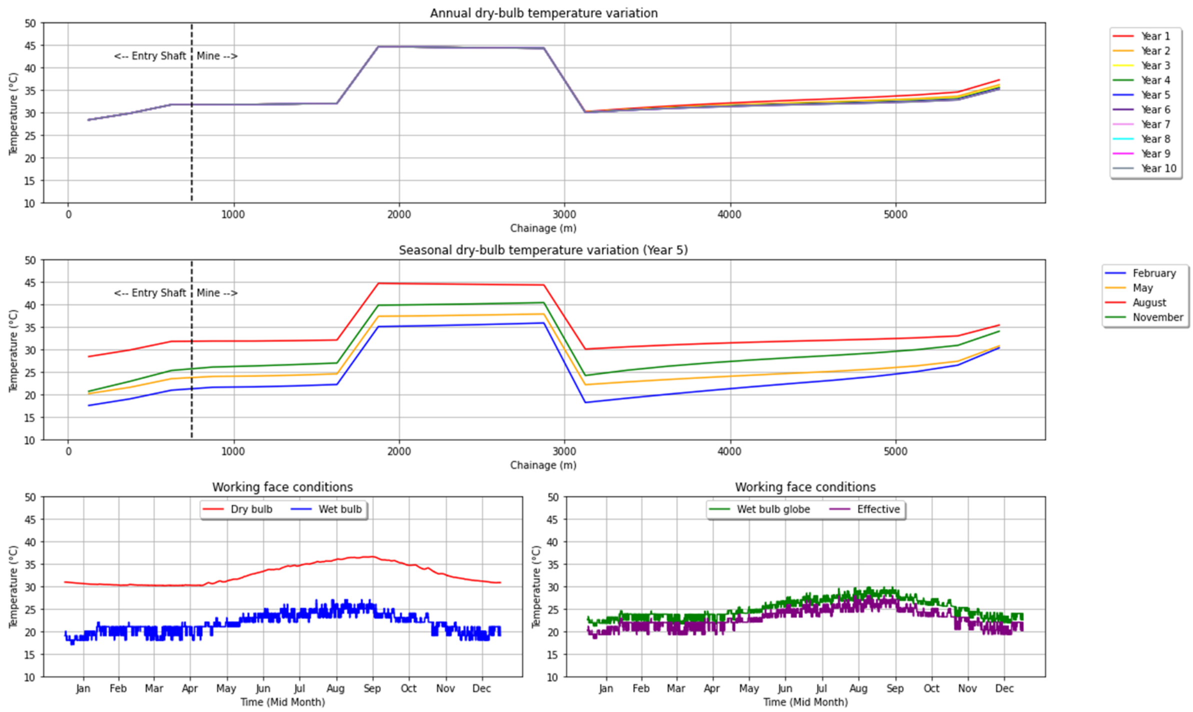

Figure 5: 2.5 MW Deep in mine cooling temperature results