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Managing Heat in Underground Mines: the Importance of Incorporating the Thermal Flywheel Effect into Climatic Modeling

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Abstract

Understanding the effects of various ventilation and climatic parameters on the work conditions and comfort in underground mines is critical for efficient ventilation system design and cost savings and to ensure the health and safety of mine workers. To understand the effects that the thermal damping effect (TDE) and the thermal flywheel effect (TFE) have on the ventilation system design and potential cooling system, this paper compares and analyzes the wet and dry-bulb temperatures at the bottom of an intake shaft using two modeling software packages, Ventsim™ and Climsim™. The comparison shows the consequences and importance of taking into account the TDE/TFE when predicting the climatic conditions in future underground mines, especially when deciding on whether a cooling system should be employed in order to provide adequate climatic conditions in the production stopes, dead-end development headings, and throughout the mine. Ventsim™ is able to account for the TFE, while Climsim™ does not. Both software packages have their uses and are used within the mining industry, but it is useful to understand their limitations and where the future of underground climatic modeling will lead.

Keywords Ventilation · Climatic modeling · Thermal flywheel effect · Mining · Health and safety · Heat

1 Introduction

Managing heat in underground metal mines is crucial for cost savings, the health and safety of mine workers, and the overall efficiency of the mine. There are important ventilation and climatic parameters which affect mine environments, but the main focus of this paper is the importance of taking into account the thermal flywheel effect, or the thermal damping effect when trying to predict the work conditions in newly developed orebodies or future underground mines. The design of auxiliary ventilation, primary ventilation, and cooling systems rely on accurate intake air parameters (e.g., wet-bulb, dry-bulb, relative humidity), as the climatic conditions in the production areas are affected by the parameters of the fresh air entering the auxiliary ventilation systems. So, if the temperatures at the bottom of the shaft are predicted too high, the auxiliary ventilation system or potential need for cooling will be overestimated, and if the temperatures predicted at the bottom of the intake shaft are too low, the system will be underdesigned, thus affecting the work conditions in the production stopes and throughout the mine.

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2 The Importance of the Thermal Flywheel Effect When Sizing a Cooling System

The thermal flywheel effect (TFE) and the thermal damping effect (TDE) are essential elements in mine ventilation and underground environment control, which significantly affect the climatic environment in deep underground mines. When air descends an intake shaft, its lining and the surrounding strata will emit heat during the night when the incoming air is cool and, on the contrary, absorb heat during the day if the air temperature becomes greater than that of the strata temperature [1]. This heat transfer process can be understood by Fourier's Law seen in Eq. (1) below:

$$q = -kA\frac{d\theta}{dx} \tag{1}$$

where,

q is the heat flux [W]
A is the area through which q passes [m^2]
k is the thermal conductivity [W/(m°C)]
θ is the temperature [°C]
x is the vertical distance [m]

The thermal conductivity, k, is a slowly changing function of temperature. The depth of the intake shaft where heat flow reverses varies by season (to some extent even daily), firstly due to the initial starting conditions of the air (T_d dry-bulb temperature, T_w wet-bulb temperature, BP barometric pressure) and secondly due to the rock surface temperature and its geothermal gradient. The change of the phase angle of the periodic, harmonic, and temperature variation is known to be the thermal flywheel effect [2]. For example, during summer, as heat from the intake air is transferred to the cooler strata, the temperature at the bottom of the intake shaft can be approximately 6 °C to 10 °C lower of what a climatic simulator with no ability to account for the thermal flywheel effect would predict [3]. This difference in the dry-bulb temperature of the mine air could lead to a significant overdesign in the capacity of the cooling system, which in some cases would make the project as economically unfeasible [4].

Climatic modeling is useful for existing operations and future operations to understand transient heat processes along vertical airways as well as predict temperature and humidity. Modeling gives engineers the ability to understand and visualize the underground mine environment and allows for more accurate predictions for critical parameters such as temperature. Even with modeling software, certain parameters, such as the TFE, are difficult to predict and understand.

The effect of surface temperatures can play a major role in the design of work comfort, ventilation, and refrigeration strategies in underground mines [5]. A comparison of two ventilation software packages, Ventsim™ and Climsim™, were conducted for Mine A, which is an underground precious metal mine in Nevada. The goal of this software comparison is to quantify the effects of the thermal flywheel in an underground mine. Ventsim™ has the capability to take into account the thermal flywheel effect, while Climsim™ does not. The Ventsim™ model used for simulation and analysis is the most current model for Mine A, which was validated versus collected ventilation and climatic data. The importance of the comparison of these software packages is to quantify the impact of incorrectly predicted mine air temperatures (T_d, T_w) when designing mine ventilation and cooling systems. Without accurate assumptions or predictions of the climatic conditions underground, there can be serious negative consequences in terms of health, safety, and expense for the mine.

It is known that the thermal flywheel effect is present within Mine A based on the data presented in Fig. 1. The thermal flywheel effect can be seen by the damping and offset of the data at the bottom of the shaft when compared with the surface data. The time delay offset is represented by the arrows and dashed lines. The damping effect can be seen by the reduction in amplitude when comparing the shaft top and bottom for both T_w and T_d.

2.1 Model Development Using Ventsim™

To model the thermal flywheel and thermal damping effect in Ventsim™, the annual flywheel heat selection mode is used. Table 1 shows the parameters used for the thermal flywheel calculation for Mine A. Many of the parameters used were predetermined from the ventilation model provided for our use. The modeling work was completed for one of the mine's intake production shaft. The values for "automatic variance," "dry-bulb maximum," "dry-bulb minimum," "wet-bulb maximum," and "wet-bulb minimum" are not used in the calculation for the annual thermal flywheel, as they are only used for daily thermal flywheel calculations. The selections of "summer dry-bulb" and "summer wet-bulb" were established based on the average temperature for the summer (e.g., June, July,

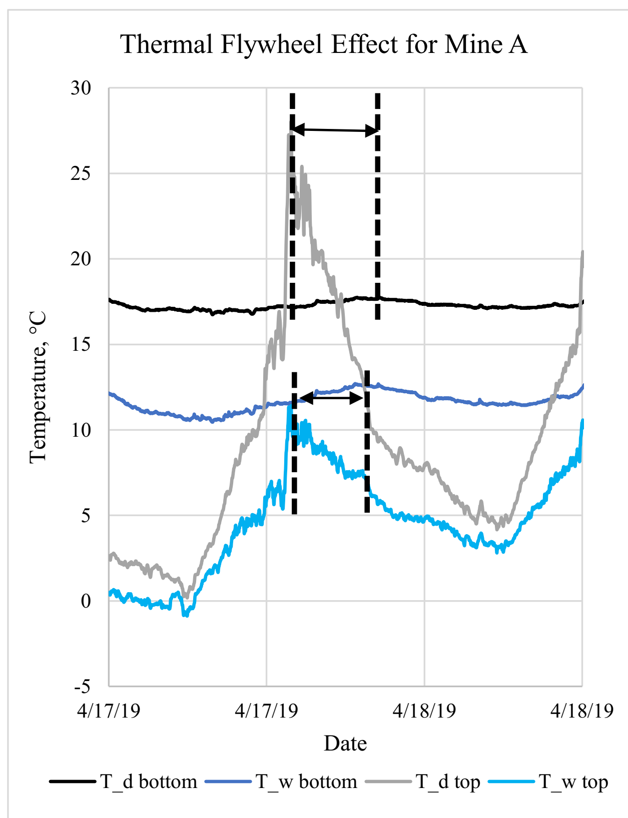

Fig. 1 Thermal flywheel effect and data for Mine A

Table 1 Thermal flywheel parameters for Mine A for input into Ventsim™. Temperatures shown are at the surface as inputs into the Ventsim™ model

Thermal flywheel	
Automatic variance	− 1.11 °C
Diurnal cycle time hours	24
Dry-bulb maximum	26.7 °C
Dry-bulb minimum	10.0 °C
Summer dry-bulb	21.7 °C
Summer wet-bulb	12.0 °C
Warmest month	August
Wet-bulb maximum	25.0 °C
Wet-bulb minimum	4.78 °C
Winter dry-bulb	−0.67 °C
Winter wet-bulb	−2.44 °C

and August) taken from the National Weather Service Forecast Office. The warmest month from the climatic data showed the warmest month as August. The selections of "winter dry-bulb" and "winter wet-bulb" were established based on the average temperature for the winter (e.g., December, January, and February) also taken from the National Weather Service Forecast Office [6]. The output data generated through ventilation and climatic simulations was recorded and compiled in imperial units, as the model validation work was performed using ventilation and climatic data provided in imperial units. However, all inputs and outputs were converted into the System International (SI) units.

Figure 2 shows the simulation results from model runs with thermal flywheel effect incorporated. The solid red and blue lines shown in Fig. 2 are the dry-bulb temperature and wet-bulb temperature of the mine air at shaft bottom, respectively. The dashed red and blue lines are the dry-bulb temperature and the wet-bulb temperature of surface air, respectively. The output data shows the effects of thermal damping (decrease in amplitude) on the mine air, and how this phenomenon can be quantified and displayed, while the presence of phase shift would require the input of thermal history data into a ventilation-thermal-humidity (V-T-H) model using an adequate software package. The vertical length of the shaft is approximately 539 m.

2.2 Model Development Using Climsim™

The importance of taking into account the effect of thermal flywheel when predicting the climatic conditions in future underground mines, the dry-bulb temperature and the wet-bulb temperature generated by Ventsim™ and Climsim™ at the bottom of the intake shaft were compared and analyzed. Again, it is mentioned that the Climsim™ program does not have the ability to take into account the effects of thermal flywheel or thermal damping. Two seasons were considered for comparison, namely, (1) summer and (2) winter. Table 2 shows the geometrical elements and other parameters of Mine A's intake shaft, which were entered into the Climsim™ software package.

Tables 3 and 4 show the simulation results generated by running the Climsim™ model. During summer, the dry-bulb temperature and the wet-bulb temperature at the bottom of the intake shaft are 33.8 °C and 29.1 °C, respectively. During winter, the dry-bulb temperature and the wet-bulb temperature at the bottom of the intake shaft are 31.4 °C and 28.1 °C, respectively.

2.3 Ventsim™ and Climsim™ Comparison

Simulation results generated through model runs developed using Climsim™ and Ventsim™ are shown in Table 5. This table shows the wet-bulb temperature and the dry-bulb temperature at the top and at the bottom of the intake shaft generated by Climsim™ and Ventsim™.

Table 5 shows that the dry-bulb temperature and the wet-bulb temperature at the bottom of the production shaft predicted by Climsim™ are significantly different than those predicted by Ventsim™, which are attributed to the effects of thermal damping. During summer, the difference between the dry-bulb temperature at the bottom of the shaft and the dry-bulb temperature at the top of the shaft predicted by Climsim™ is

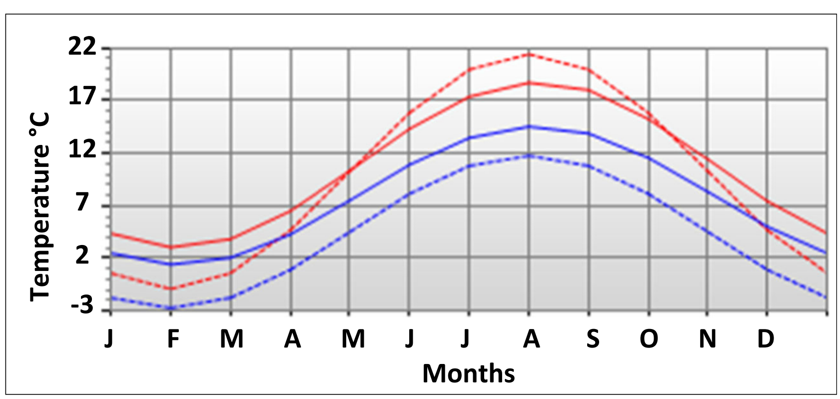

Fig. 2 Thermal flywheel modeling output for Mine A from Ventsim™

Table 2 Input parameters for Mine A into Climsim™ with pressure and airflow quantity representing values at the top of the shaft

Pressure (kPa)	102
Quantity (m^3/s)	261
Length (m)	539
Area (m^2)	23.6
Perimeter (m)	17.2
Friction (kg/m^3)	0.042
Wetness	0.50
VRT in (°C)	10.0
Geothermal step (m/°C)	16.0
Rock conductivity (W/m °C)	4
Diffusivity ($m^2/s \times 10^{-6}$)	1.75

Table 4 Results for Mine A's intake shaft—winter

Winter		
Parameter	Top	Bottom
Dry-bulb (°C)	0.00	31.4
Wet-bulb (°C)	0.00	28.1
Humidity (%)	100	77.5
Enthalpy (KJ/kg)	9.41	87.1
Sigma Heat (KJ/kg)	9.41	84.5
VRT (°C)	10.0	43.7
Strata—latent heat (kW)	0.00	14,600
Strata—sensible heat (kW)	0.00	9030

approximately 12 °C, while Ventsim™ estimated a difference of − 4.6 °C. The negative value means that the temperature at the bottom will be lower than the air temperature at the top of the shaft, as heat is transferred to strata. During winter, the difference between the dry-bulb temperature of the air at the bottom of the shaft and the dry-bulb temperature of the air on surface predicted by Climsim™ is approximately 31.4 °C, while Ventsim™ estimates a difference of only 5.50 °C, as heat is transferred from strata to the ventilating air.

This large discrepancy between Ventsim™ and Climsim™ output data is largely due to the thermal flywheel effect. During summer, the temperature of the ventilating air has elevated values due to both the high air temperature on surface and to the heat added by auto-compression. Because the air temperature on surface is higher than the strata temperature, heat flows from the ventilating air into the strata; thus, the temperature of the ventilating air decreases as it downcasts the shaft. In the winter, heat stored in the strata is released back into the ventilating air since the temperature of the strata is higher than the temperature of the ventilating air downcasting the shaft. Thus, the temperature of the ventilating air increases as it flows down the shaft. However, at a certain depth, due to the geothermal gradient, the temperature of the strata becomes higher than the temperature of the ventilating air. As a result, heat will flow from the strata to the ventilating air.

Table 3 Results for Mine A's intake shaft—summer

Summer		
Parameter	Top	Bottom
Dry-bulb (°C)	21.7	33.8
Wet-bulb (°C)	12.0	29.1
Humidity (%)	29.2	70.3
Enthalpy (KJ/kg)	33.7	91.6
Sigma heat (KJ/kg)	33.5	88.9
VRT (°C)	10.0	43.7
Strata—latent heat (kW)	0.00	13,400
Strata—sensible heat (kW)	0.00	2230

Data collected at Mine A within the date range of April 18, 2019, to April 19, 2019, shows that the average wet-bulb temperature (T_w) was 13.9 °C. This value can be compared with model outputs to show the significance of modeling the thermal flywheel effect. The T_w output for Climsim™ only showed values for summer (29.1 °C) and winter (28.1 °C), but the values did not fluctuate much for the seasons. If we average these outputs to obtain a simple prediction for April, the T_w would be 28.6 °C. The T_w output for Ventsim™ was 6 °C during mid-April, as seen in Fig. 2. The comparison and differences of the models to data can be seen in Table 6.

The negative values for "model error" in Table 6 would indicate an under-designed system because the system would be designed based on a lower temperature creating an unsafe thermal climate. The positive "model error" shown for Climsim™ would be significantly overdesigned, leading to a system that costs large monetary sums.

We can conclude that in respect to the underground mine climate, if Mine A's cooling system would be designed on the output data generated by Climsim™, the cooling system would be significantly overdesigned, which would likely result in large capital and operating costs. As a result, the "thermal flywheel effect" must be taken into account when designing and sizing a cooling system whether installed on surface or underground. While Ventsim™ is more accurate and accounts for the TFE, it still has errors accounting for the TFE phase shift associated with Mine A when compared with the collected climatic data.

3 Conclusion

As many metal mines deepen, a different approach might be needed to reduce the temperature of the ventilating air.

Table 5 Comparison of results for wet-bulb and dry-bulb temperatures generated by Climsim™ and Ventsim™

Location	Climatic parameter	Climsim™		Ventsim™	
		Mine A summer	Mine A winter	Mine A summer	Mine A winter
Top	Wet-bulb	12.0	0.00	12.0	0.00
	Dry-bulb	21.7	0.00	21.7	0.00
Bottom	Wet-bulb	29.1	28.1	13.3	3.56
	Dry-bulb	33.8	31.4	17.1	5.50

Temperatures in °C

Exposure to high levels of heat and humidity can significantly affect health and safety, as well as productivity in underground mines, and therefore, a correct estimation of the mine air temperature is necessary. To accurately predict the dry-bulb temperature and the wet-bulb temperature at the bottom of vertical intake airways (e.g., production & ventilation shafts), the thermal flywheel effect must be taken into account when designing and sizing the primary and secondary fans of the ventilation system, or a potential refrigeration plant to avoid additional capital and operating costs as well as maintaining safe underground conditions for mine workers. Both softwares mentioned have their usefulness within the mining environment, but they both have their limitations. While Ventsim™ can account for the TFE, it is still only a temperature prediction model. More up-to-date and continuous temperature data from the surface and bottom of the shaft would be useful to keep the Ventsim™ model up to date and validated. The future of climatic modeling will likely depend on analyzing large datasets and integrate the ability to predict climatic conditions from measured data. The application of neural networks allow for even more accurate predictions of the underground thermal environment [7].

Table 6 Comparison of results for wet-bulb temperatures generated by Climsim™ and Ventsim™ compared to Mine A data in April

	Mine A shaft bottom temperatures		
	Data	Ventsim™	Climsim™
T_w (°C)	13.9	6	28.6
Model error (°C)	–	− 7.9	14.7

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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