COMPREHENSIVE HEAT STUDY AT A WYOMING UNDERGROUND TRONA MINE

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ABSTRACT

The FMC Westvaco Trona Mine is located near Green River, Wyoming and has an annual production of 4.5 M tons. The underground mine has three active development panels and one longwall panel. The mining horizon is about 500 m below surface and strata liberate methane. Three surface-based blowing fans provide ventilation air. A ventilation survey and subsequent analysis was undertaken and a simulation model developed. Air heating during winter is essential to prevent freezing of pipelines and to lesser degree, for miner comfort. Air at all three intake shafts is heated using gas-fired heat exchangers.

A strata heat study was conducted in one of the active panels to determine rock attributes. Tests included in-situ measurements of rock thermal conductivity and geothermal gradient. Continuously methane monitors have also been installed in an active development panel's return drift. Ventsim ventilation software was used to aid the heat and contaminant simulation study. An exercise was also undertaken to gain some understanding of methane contaminant levels throughout the mine. It was further used to determine an adequate surface intake air heating rate and consequently the minimum natural gas consumption needed for winter intake air heating at the mine.

KEYWORDS

Strata heat, Contaminant simulation, Air heating rate, Optimization

INTRODUCTION

Rock thermal properties determinations are important in studying heat transfer, water balance and mass exchange processes occurring across porous media surfaces. The study of heat transfer is of significance in understanding thermal behaviour, especially in relation to determining underground heat flux. The surface heat transfer coefficient, h, is a measure of the rate of heat transfer from rock to the ventilating air or in the opposite direction. It is of particular importance in the determination of the thermal flux into the ventilating air in underground openings in the early stages of rock cooling after excavation (Vost, 1973). The conduction heat transfer is governed by Fourier's law (equation 1). Determining the heat flux requires knowledge of the manner in which temperature varies within the medium, the temperature distribution, (Incopera et al., 2007). The rate of heat conduction, *q*, is proportional to the temperature difference across the boundary layer of air between the rock surface and the main air stream, and is given by the following equation

$$q_x = -kA\frac{dT}{dx} \tag{1}$$

where *k*, the thermal conductivity (W/m.°K) is an important thermal property of material. Heat flux, though, is a vector quantity hence the equation can be written as a more general statement of the conduction rate equation (Fourier's law) as follows:

$$q^{\uparrow=} = -k\nabla T = -k(i\,\partial T/\partial x + j\,\partial T/\partial y + k\,\partial T/\partial z) \tag{2}$$

where ∇ is the three dimensional Del operator and *T*(x.y.z) is the scalar temperature field.

An in-situ borehole measurement method called REKA (Rapid Evaluation of k and alpha), has been proposed by Danko and Cifka (1985), and further developed, tested, and applied by Danko, Mousset-Jones and McPherson (1987). There are a variety of laboratory measurement methods and sophisticated procedures for obtaining thermal conductivity and diffusivity for samples of rock taken from an underground mine. The accuracy of the methods is dependent upon the sophistication of the equipment and the care taken in the measurement process. A study by Danko et al. (1987) was conducted to evaluate how representative values obtained in the laboratory for thermal conductivity and diffusivity are when compared to their actual in situ values as published later by (Danko & Mousset-Jones, 1989). The in situ rock mass surrounding a mine roadway is subject to a variety of effects usually not present in a laboratory sample such as the presence of water with or without filtration, vapour and non-condensable gas movement, rock stress, micro and macro fractures, inherent non-homogeneity of the rock mass, strata bedding and so on. However, the major effects upon the thermophysical properties are those caused by moisture content.

Initial ventilation and heat flow studies at FMC mine showed that heaters would be required to maintain acceptable intake shaft temperatures. The detailed studies were conducted to accurately quantify the expected heat load requirement. During the initial heat flow analyses certain tests had been undertaken for evaluation of the strata heat load. These tests included the estimation of the rock thermal properties and virgin rock temperatures (VRT). The determination of three critical parameters, the rock thermal conductivity (k), the rock thermal diffusivity (α) and the geothermal gradient are discussed in the paper. Ventsim Visual simulation software was used and heat simulations conducted.

IN-SITU ROCK THERMAL CONDUCTIVITY MEASUREMENTS

Measurement Site Description

Virgin Rock Temperature

The increase in the VRT of strata (unaffected by underground activities) with respect to depth is known as the geothermal gradient. It is the linear increase in depth for each unit increase in temperature. The geothermal gradient varies according to the local rock's thermal conductivity and the depth of the earth's crust in the area (Duckworth, 2010). In order to evaluate strata heat flow in subsurface environments it is vital that the geothermal gradient is determined

Data on the natural rock temperature at a known elevation is required to measure VRT. At FMC mine a 6 m long, 40 mm diameter hole was drilled by a jumbo rock drill. The hole was drilled into the fresh air course close to the face (23 m outby the last open cross cut). Two thermocouples were inserted into the hole immediately after the hole was drilled. One thermocouple was placed at the hole's bottom-end (6 m from the hole collar) and the other was placed 3 m from the collar (Figure 1). The elevation at site location was 1437 m above sea level and the rock had been mined and exposed four days before the measurements were taken.

The VRT test was undertaken in the development panel. The hole was sealed from the atmosphere with urethane foam to avoid intake air affecting the results. Every effort was made to insert the probe into the hole as soon as possible after drilling. The probes were connected to a laptop computer and thermocouple readings were logged for four full shifts (equivalent to 1800+ min). The rock temperature values started dropping shortly after the probes were inserted into the hole. The energy absorbed by the rock during drilling was considered enough to significantly raise the temperature of the rock mass. The test was conducted in early August when the local surface temperature, outside the mine, was 30 °C. The results show the test location ambient air temperature is higher than the VRT. This indicates the air would lose heat resulting in lower temperatures while it is travelling through the underground until both temperatures reached the same value. The VRT temperature was determined to be 26 °C.

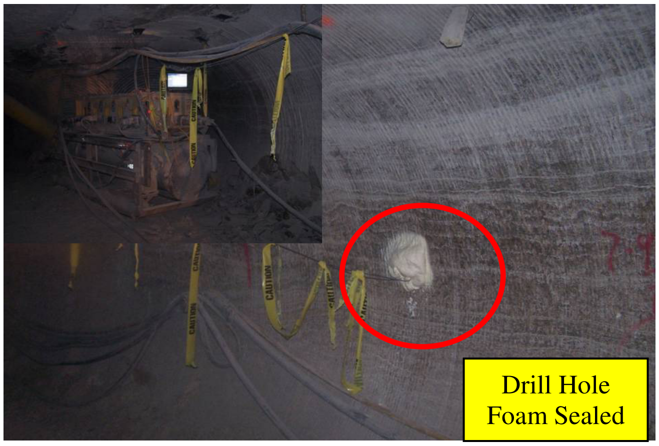

Figure 1 – Virgin rock temperature experimental station and drilling equipment (in inset)

Rock Thermal Conductivity Test

An array of thermocouples was installed in boreholes to measure Rock Thermal Conductivity (k). These boreholes were located relatively close together in a drift within the LW-9 development panel which were driven with a Bore Miner machine. The finished oval dimensions are 4.8 m by 2.5 m. Seven, 2.75 m long holes were drilled in the rib with a jumbo rock drill. Thermocouples and a heater were installed in these boreholes. The spacing in between the holes was 340 mm. One of the difficulties encountered with these measurements was drilling the boreholes parallel to one another to increase the accuracy of the test. The drift length was 75 m. Figure 2 shows the conductivity test site and borehole details. Four horizontal holes were drilled, two on each side of center hole. During the test, the air velocity, pressure and temperature of the drifts were monitored at both ends.

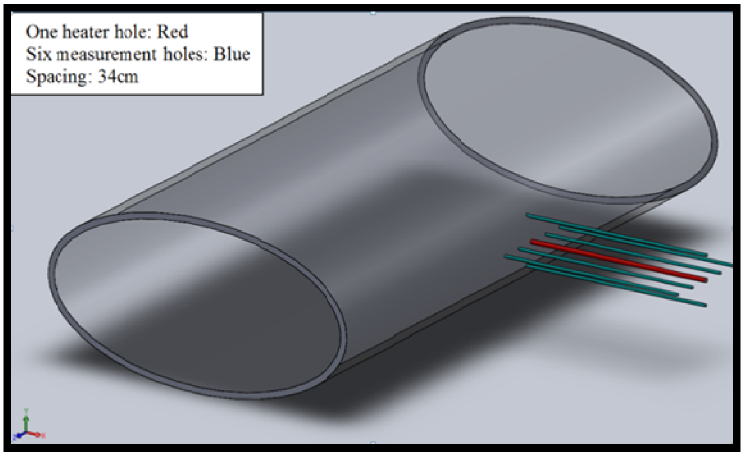

Figure 2 – Outline of rock thermal conductivity test

Two pressure transducers with manufacturer's quoted accuracy of ±8 Pa were used to monitor the pressure difference in the drift. In addition, two thermocouples were used to monitor the temperature during the test with thermocouples plugged into a laptop computer by running long wires. Air velocity readings were taken during the test by using an anemometer traverse method. The air velocity range was between 0.6 and 0.75 m/s. Figure 3 shows the pressure and temperature in the test area. The pressure transducers were positioned on the ground while the thermocouples were hung 0.5 m from the roof. The thermocouples accuracy was quoted by the manufacturer as within ±1 degrees.

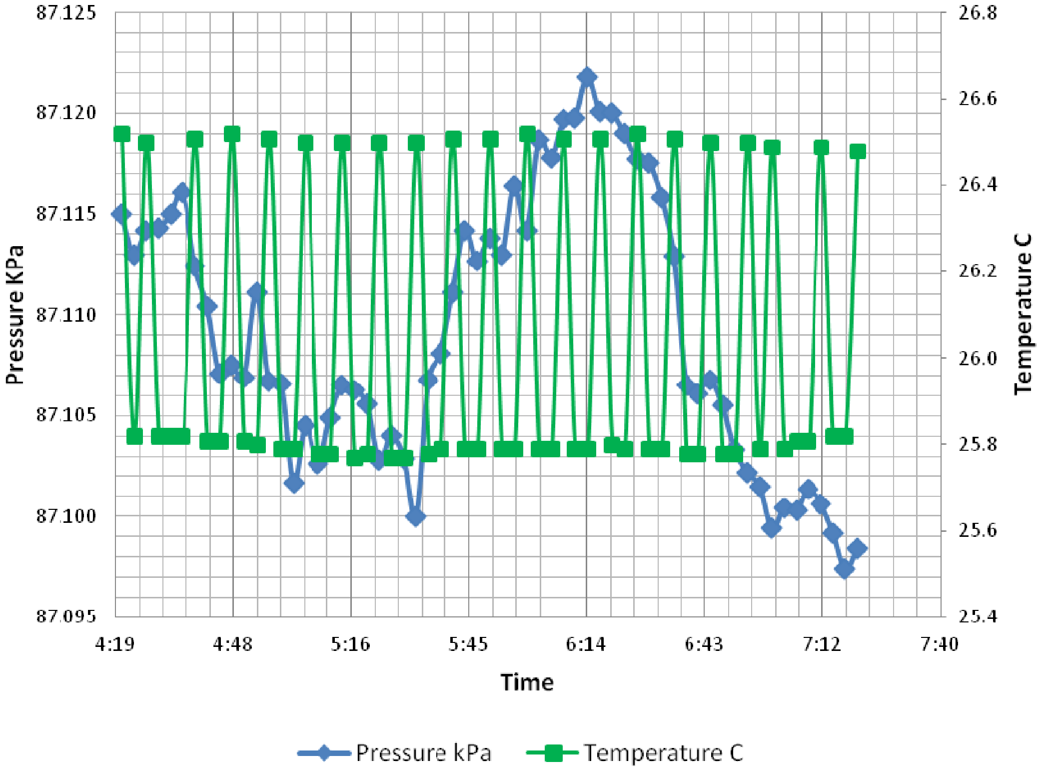

Figure 3 – Pressure and temperature readings in the test location

The center hole was a drilled at 34mm diameter and wider than the other holes as shown in figure 4. A 5.5 m long heater cable with rated heat generation rate of 3000 W was folded and sunk into this center hole. The heater was supplied with 220 V. The actual output heat generation rate was 2,750 W pulling 12.5 amps at 220 V. A 1.2 m long thermocouple was put in the center hole to monitor and control the temperature. Both the heater and the thermocouple were plugged into the digital controller that acted as the thermostat. The center borehole was controlled at the adjusted temperature to provide a uniform temperature in the hole. A datalogger was used.

In addition to the center hole six 2.75 m long horizontal boreholes with spacing of 34 cm were drilled to monitor the temperature adjustment in adjacent holes. The diameter of the adjacent holes was 22mm. Every effort was made to minimize the space in between the thermocouples and the walls of holes. The thermocouples were tied to the flexible wires to ensure the surface contact of thermocouple's tip and the wall. The four holes that surrounded the center hole had two thermocouples each. The boreholes were sealed by silicon to reduce the convective heat transfer within the hole. Figure 4 shows the k test set-up. Additionally an infrared thermometer was used to monitor and measure the surface rock temperature. The first thermocouple in each hole was placed at 1.2 m from the collar where the second was placed at 2 m. The values obtained were then used to determine the convective heat transfer from the wall to the drift environment. The values obtained were used to determine the rate of heat transfer from the center hole to the adjacent thermocouple holes and hence the rock's conductivity.

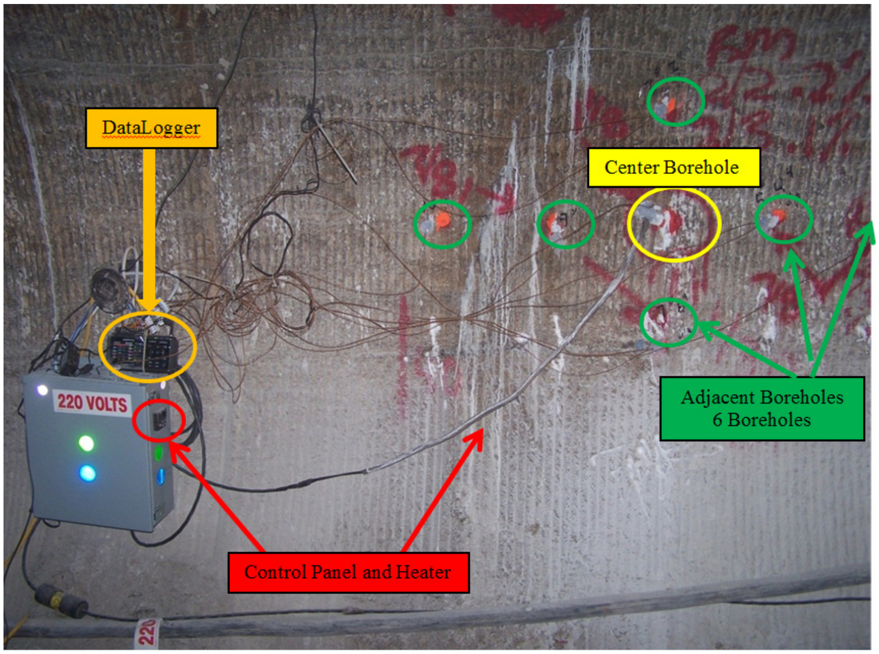

Figure 4 – K test site set-up

Data Analysis and Equations

Rock thermal conductivity is a measure of the ability of material to transfer heat. For steady state conditions, the k value for a straight drift may be measured from the following equation (Mousset-Jones, 1988):

$$\frac{(T_2 - T_1)}{\log_e(\square]\,[\frac{r_2}{r_1})} = -\frac{q}{2\pi kl} = b \qquad (3)$$

where: r = radius from center of drift (m); T = temperature (°K) at location r; q = radial heat flow (W); L = length of test section (m); and b = slope of graph of T v. $\log_e$ r.

Cylindrical and spherical systems often predominantly experience temperature gradients in the radial direction only and may therefore be treated as one dimensional. In many instances, two-dimensional or three-dimensional conduction problems may be solved by utilizing existing equations. These solutions are reported in terms of a *shape factor*, S, or a steady state *dimensionless conduction heat rate* (Incopera et al., 2007). For the purpose of this paper the following method has been used to analyze the data.

The heat transfer rate may be expressed as:

$$q = Sk\Delta T_{1-2} \qquad (4)$$

where ΔT_{1-2} is the temperature difference between boundaries.

The *S* value was obtained analytically for numerous 2 and 3-dimensional systems and configurations. This equation was selected since it has been assumed that the 2-dimensional conduction occurs between the boundaries that are maintained at uniform temperatures. In other words, the conduction between cylinders (boreholes) of length L is simulated as being in an infinite medium (the strata rock).

$$S = \frac{2\pi L}{\cosh^{-1}\left(\frac{4w^2 - D_1^2 - D_2^2}{2D_1 D_2}\right)} \qquad L \gg D_1, D_2 \quad \& \quad L \gg w \tag{5}$$

Where D_1 and D_2 are the center and adjacent borehole diameters (m) and w is the spacing in between the boreholes (m). The known heat transfer and calculated S then could be substituted in the following equation and the k value determined.

$$q = Sk(T_1 - T_2) \tag{6}$$

In heat transfer analysis, the ratio of the thermal conductivity to the heat transfer capacity is an important property termed the thermal diffusivity α, in m^2/s:

$$\propto = \frac{k}{\rho c_p} \tag{7}$$

Convection heat transfer values were also obtained. The drift surface temperature has been monitored by using temperature infrared sensors. The surface is presumed to be a flat plate at uniform temperature, T_s. With increasing distance from the leading edge the effects of heat transfer penetrate further into the fluid and the thermal boundary grows (Incopera et al., 2007). The surface heat flux and convection heat transfer coefficient both vary along the surface, A_s. The total convective heat transfer could be determined by using average convection coefficient, h.

$$q = hA_s(T_s - T_{air}) \tag{8}$$

At air velocities > ~ 0.3 m/s the relationship may be taken as a straight line (Gillies et al., 1991):

$$h = 4.87V + 2.43 \tag{9}$$

where V is the air velocity (m/s).

This line has a correlation coefficient of 0.98 with as Gillies suggested based on analogy with flow in smooth pipes:

$$h = 6.76V^{0.8} + 0.74 \tag{10}$$

At air velocities of 0.4 m/s or above, as occurred during this study, the values of h may be derived from equation 9 (Gillies et al., 1991) giving a heat transfer coefficient of 5.3 W/m^2 °K.

Using equation 8, with the rock air temperature up and downstream of the boreholes surface temperature determined to be 350° K , the convective heat transfer has been calculated to be 620 W.

The quantification of heat transfer in the infinite medium can be calculated by subtracting the calculated convective heat transfer from the total heat transfer. The total heat transfer rate can be obtained from the power equation as well. The current on the heater was monitored so the measured amperage could be substituted in the equation:

$$P = VI \tag{11}$$

where P is the power (W), V is the voltage (220 V) and I is the amperage drawn.

Table 1 shows the rock Trona's determined thermal properties. These can be made use as constants for input into the Ventsim software.

Table 1 – Thermal properties of Trona

Property	Value unit
Rock density	2130 kg/m^3
Rock thermal conductivity	4.5 W/m ° K
Rock thermal diffusivity	1.68×10^{-6} m^2/s
Rock specific heat	1260 J/kg ° K

PRESSURE QUANTITY AND TEMPERATURE SURVEY

A comprehensive Pressure Quantity (PQ) survey was conducted throughout the mine. The surface barometric air pressure was monitored and recorded during the survey. Figure 5 shows the surface pressure and temperature change readings. The surface and underground temperature readings were used to determine the heat generation rate at surface heat exchangers.

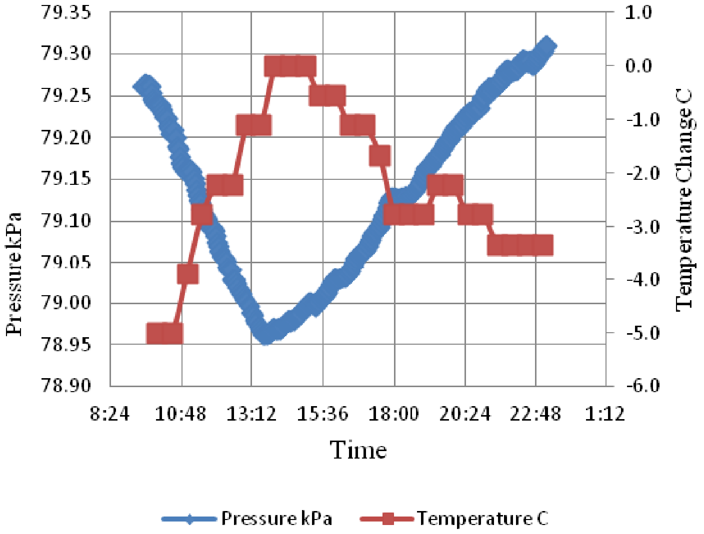

Figure 5 – Surface pressure and temperature readings

Temperature readings taken from the intake shafts (Shaft Numbers 5, 8 and 7) recordings were used to estimate heat generation by surface heaters (Table 2), and used in Ventsim airflow and heat simulations.

Table 2 – Estimated heat generation rate at surface heaters

Shaft	Airflow m^3/s	Temperature (°C)		Density (kg/m^3)		Heat generation rate (kW)
		Outside	At the elbow	Surface	Underground	
5	234	-3.4	14	1.0254	1.0142	4,800
7	132	-3.2	12.3	1.0264	1.0085	3,134
8	200	-4	17	1.0260	1.0115	5,502

A temperature survey was conducted and results were analyzed. The mine's pump stations were identified as the highest underground heat source category (Habibi et al., 2013). Table 3 shows total heat generation rate in some of the pump stations. The assumption of 80 % motor efficiency was used for power calculations. Most of the pumps were not running continuously; therefore the heat input numbers have been slightly lowered.

Table 3 – Pump stations power usage

Pump station	Power (kW)	Heat (MJ/h)
5 Shaft	895	3,220
349	522	1,878
Bypass	261	939
3 NE	261	939
2 NW	112	402
7 Shaft	186	671
3 Shaft	298	1,074
Total	3,054	10,986

Ventsim Simulation Calibration and Results

The ventilation simulation model was built from the mine's existing AutoCAD model. The model consists of 26,725 airways with total length 983 km. The Ventsim model was calibrated against pressure, quantity and temperature results. The model simulation predicted results agreed to within 9 % accuracy of the actual measurements which is considered an acceptable accuracy for both flow and temperature. Figure 6 shows the key stations and the ventilation stations and corresponding distances. The survey results show that the temperature increases up to 8 ° C by the time air gets to the Longwall headgate. Table 4 shows the ventilation survey results against the measurements at important key stations.

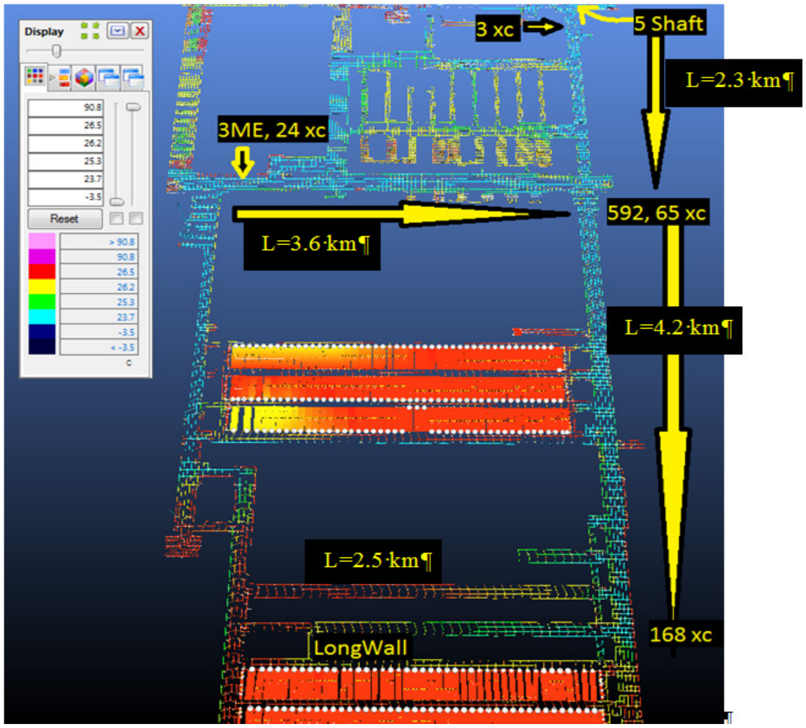

Figure 6 – Heat simulation schematic view

Table 4 – Predicted Ventsim results vs. actual measurements

Station	Temperature (°C)		Airflow (m^3/s)		Difference	
	Ventsim	Measurement	Ventsim	Measurement	Temp	Q
592, 3 XC	17.3	18.6	57	52	7.5	8.7
3ME 24 XC	22.4	23.5	35.5	32	4.9	9.8
592, 65 XC	22.1	23.6	36.3	39	6.7	7.4
592, 168 XC	24.6	26	32	35	5.7	9.3

The Natural Ventilation Test

The natural ventilation pressure and compressibility of the air were taken into account in simulations. A simulation was conducted for a case where all the surface fans were off. The results were compared against experimental measurements that were taken during a mine-idle shift with fans off. The simulation and experimental data are shown in Table 5. The surface dry bulb temperature was 4.4 ˚ C.

Table 5 – NVP Ventsim simulation results vs experimental results

Shaft	Ventsim simulation results		Experimental results
	Air direction	Quantity (m^3/s)	
1 Shaft	Down cast	1.9	Down cast
2 Shaft	Down cast	12.6	Down cast
3 Shaft	Down cast	15.8	Down cast
4 Shaft	Down cast	29.2	Down cast
5 Shaft	Up cast	19.8	Up cast
6 Shaft	Down cast	15.5	Down cast
7 Shaft	Up cast	18.3	Up cast
8 Shaft	Up cast	21.5	Up cast
9 Shaft	Down cast	3.8	Down cast

RESULTS AND DISCUSSIONS

Surface Heating Rate

The Ventsim simulation and temperature survey results have been used to adjust the surface heat generation rate and optimize the natural gas consumption rate. The survey results show that there is an opportunity to reduce the amount of heat input from 8 Shaft heaters. 8 Shaft is the main access and transportation shaft in the mine. A temperature above freezing needs to be maintained at the collar of the shafts to protect pipes. The pump stations need some means to remove generated heat. By reducing the heat input at 5 and 8 Shafts down to 4,200 kW in both shafts, the temperature at the shafts and working faces could still be maintained by making use of strata heat. The Ventsim airflow and heat simulation results show in this circumstance that the temperature would be 13 °C at the bottom of the 8 Shaft, 21.5 °C at 592 65 XC and 24.1 °C at the LW Headgate. This significant drop in heat generation rate of (2100 kW) at the shafts would reduce natural gas consumption by 15 %.

Blade Settings Improvement and Natural Gas Consumption Optimization

The FMC mine’s ventilation network has been improved by some changes at both the surface and underground to increase overall efficiency. One recommendation was given regarding blade settings on surface fans (Habibi et al., 2013). Figure 7 shows the blade setting being changed at 7 Shaft. The blade settings were lowered in 7 and 8 Shafts as follows:

- 7 Shaft air is being used to ventilate the sumps and pump stations to the North. Blade setting reductions (lowered by two blade settings) resulted in a significant drop in pressure, operating cost, bearing vibration, leakage and natural gas consumption.
- 8 Shaft air is being used to ventilate the main shop, LW and bore miner panels. The PQ survey results show that 5 and 8 Shafts are pushing against each other. A lower blade setting in either of their fan system would again reduce the pressure and consequently the operating costs. The 8 Shaft was chosen for a change as it is the primary transportation shaft and a lower blade setting would reduce noise and gas consumption.

Table 6 shows the 7 and 8 Shafts operating characteristics prior to and after the changes. The amp readings are being logged and recorded on all three surface fans. These show the annual operating costs dropped by 18 %. Meanwhile, the air quantities are either similar or improved. The overall air efficiency has improved by 12 %. Also as a result of the lower fan operating pressure, the pressure across the main stopping lines has also reduced which has resulted in less leakage across the stoppings. The flow reduction in 7 Shaft and 8 Shaft decreased their natural gas consumption by 13 %.

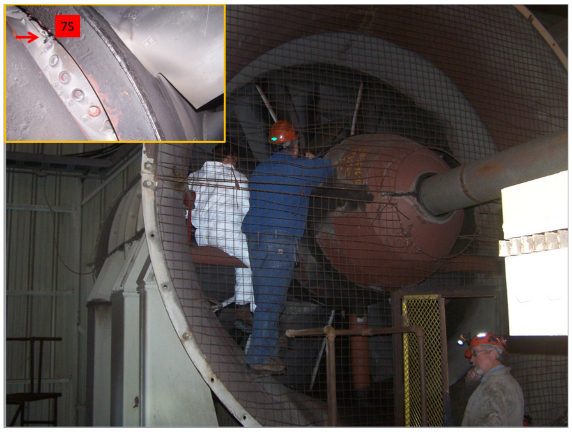

Figure 7 – Blade setting change

Table 6 –Shafts 7 and 8 fan blade settings and characteristics

Fans	Blade setting		Airflow (m^3/s)		Vibration(m/s)		Pressure (kPa)		Current drop(Amps)
	Previous	Current	Previous	Current	Previous	Current	Previous	Current	
8	4B-4S	3B-3S	209	184	0.06	0.04	1.7	1.5	12
5	4B-4S	4B-4S	202	204	0.06	0.06	1.7	1.7	3
7	2B-2S	6B-7S	160	125	0.08	0.05	1.6	1.3	24
Total			571	513					39

CONCLUSIONS

A ventilation model of the FMC mine has been built and projected to include the mine's fifteen year plan. A comprehensive PQ survey was conducted allowing a feasibility review to be completed on the alternatives available to improve working ventilation as production moves into new parts of the mine lease. Trona's rock thermal properties were measured. The VRT also was measured to calculate the geothermal gradient. The combined results were then inputted into a ventilation network modelling software package, Ventsim. The model was calibrated and the airflow and heat conditions were simulated. The study examined alternatives to improve the use of the current heat and ventilation infrastructures, seeking increased efficiencies and reduced power and heating annual operating costs.

The temperature survey results show that the air temperature decreases as it travels towards working faces. This indicates that the strata is acting as a heat sink and an unnecessary loss of the mine's natural gas heating input is occurring. The simulation results showed that overheating the air at 8 Shaft is unnecessary as the air could pick up heat while traveling through the 10 km of drifts to the working faces.

The simulations also showed the heating of intake air could be reduced in 5 and 8 Shafts while still fulfilling the requirement to avoid the freezing of services. The result from this would be a 15 % reduction in natural gas consumption.

The ventilation simulations showed that the blade settings could be changed on the surface fans while maintaining or improving volumetric deliveries throughout the mine C. Consequently the 7 and 8 Shaft fan system blades were adjusted to a lower setting without adverse effects. This change reduced the intake air quantity entering the mine by about 70 m^3/s, which created another opportunity to consume less natural gas. The blade setting change also reduced pressure delivery and vibrations from surface fans. The change in surface fan operating conditions has reduced their electrical power consumption by about 17 %.

The company has already saved power and natural gas by changing the blade setting of the surface fans. Currently, the opportunity to offset surface heating with natural gas with strata heat gains is still being considered by the company and is the subject of further studies. Additional improvements to the underground ventilation network, identified through these investigations are being planned.

ACKNOWLEDGMENTS

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