Improved understanding of a trona mine ventilation system to improve airflow and efficiency and the potential for energy savings through monitoring of barometric and natural ventilation pressures

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ABSTRACT: Barometric pressure variations have considerable impact on underground ventilation circuits, affecting airflow quantity at working faces. Natural ventilation pressure (NVP) changes can be induced by thermal energy exchange between the air and strata and also may have significant effects on airflow. A comprehensive mine ventilation survey was performed over the course of one year in the 490 m deep FMC Westvaco trona mine in Green River, WY, to develop and calibrate a numerical ventilation model of the mine, to improve the existing ventilation network model, improve air utilization and efficiency, aid long-term environmental and ventilation planning and identify energy saving opportunities. The interaction between the NVP and main fans was investigated to determine differences in seasonal power consumption. During summer, barometric pressure changes are steadier with sudden fluctuations when compared to winter. A maximum temperature of 36ºC was measured in July and the minimum of -32ºC was registered in January. The average daily temperature fluctuation is over 20ºC; and is larger in the summer with cold nights and hot days. Fan current readings show that power consumption is considerably less during summer due to higher temperatures and lower density air. Analyses of air pressure and fan current readings were undertaken to determine the effects of shaft cage movements and associated pressure changes in shafts. A pressure drop averaging 120 Pa was measured when the cage was ascending and lowered by an average of 100 Pa when descending. Fan motor current readings varied over a range of 5 A demonstrating the effect of cage movements on power consumption. Techniques improve airflow utilization and save power were made by reducing network resistance and higher efficiencies through fan blade setting changes.

1 INTRODUCTION

Natural ventilation plays an important role in the generation and distribution of airflows in underground mines. Therefore, knowledge of the magnitude of the NVP is valuable in the ventilation system control process, especially in emergency conditions such as mine fires or when surface fans have stopped due to mechanical or electrical faults (Wala, 2002).

In most underground mines, some flow of air will occur without fan assistance caused by NVP. Density difference in shafts causes the heavier fluid to displace the lighter fluid. This motion will be maintained for as long as a difference exists between the mean densities (McPherson, 1993). Transient changing conditions of a mine ventilation system are caused by both intended adjustments in the use of ventilation equipment and random disturbances (Trutwin, 2005). Some disturbances, including those resulting from fan operation, can have a considerable range and impact upon the transient process in the entire mine ventilation network (Roszkowski, 2002). The transient effects caused by seasonal and diurnal surface temperature changes, also impact the ventilation characteristics (Brunner et al, 1991). Fan pressure causes some variation in density, but since it is usually small and affect both air columns, its effect is relatively unimportant (Weeks, 1994).

2 DESCRIPTION OF MINE VENTILATION NETWORK

FMC's Westvaco mine located west of Green River, Wyoming, is the world's largest underground trona mine and producer of soda ash. The mine hoists 4.5 million tons of trona annually to eight surface processing plants. The mine is relatively shallow at 490 m and is categorized as a gassy mine (MSHA Class III). Currently the mine is being ventilated with 500 m^3/s. The air is forced into the mine by three intake shafts each fitted with a vane axial Jeffrey 8 HU-117 (2 stage) Aerodyne surface fan. There are six exhaust shafts. The air travels over 12 km from the bottom of the intake shafts into and out of the workings to the exhaust shafts.

The mine has two active continuous miner and one longwall sections. The room and pillar development panels are being driven by bore miner continuous miner machines and are comprised of four rooms with adjoining crosscuts. An internal air requirement of 5 m^3/s has been determined for each room (12 m^2) which gives a combined requirement of 20 m^3/s at the bore miner panel regulator. 50 m^3/s is also required for the longwall (LW) face, measured at 110 shield on the face, to dilute methane and keep the methane concentration below 1.0% (Code of Federal Regulations, 2014).

The south mine production area air is exhausted from Number 9, 6 and 4 Shafts. Number 4 Shaft does not play an important role due to its long distance (9 km) from active mining sections. Number 5, 7 and 8 are intake air shafts. Number 8 Shaft is used for personnel access and supplies along with 5 Shaft. Number 7 intake Shaft separately ventilates the semi-isolated north part of the mine. Figure 1 shows the mine outline and shafts.

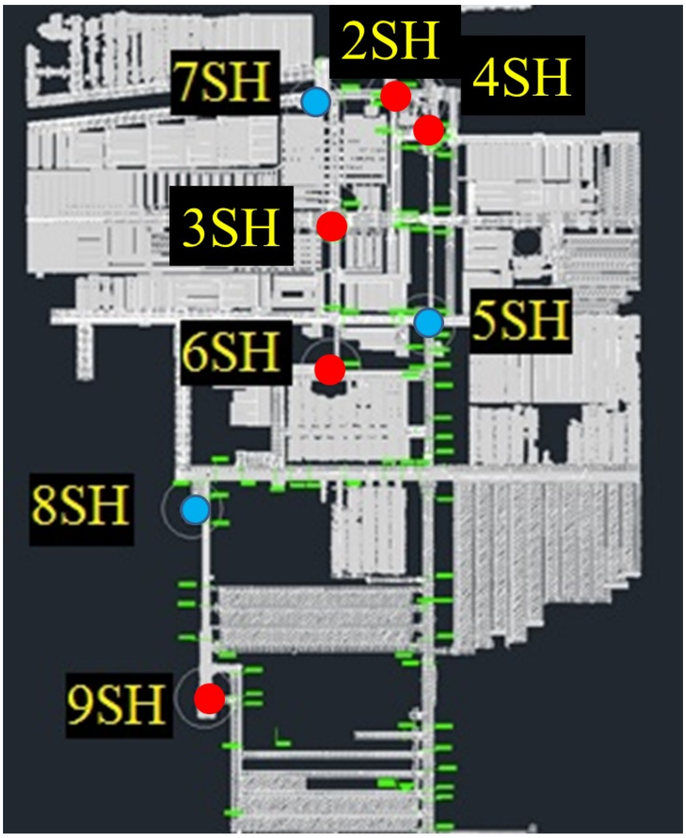

Figure 1. Mine outline and shafts.

2.1 *Seasonal pressure fluctuations*

Barometric monitoring determined that during summer months the surface pressure change is steady, with sudden fluctuations with the range of less than 50 Pa. However, during winter the magnitude of change is considerably larger. A pressure fluctuation of 175 Pa was registered. Figure 2 and Figure 3 show the pressure and temperature fluctuations in the course of one year.

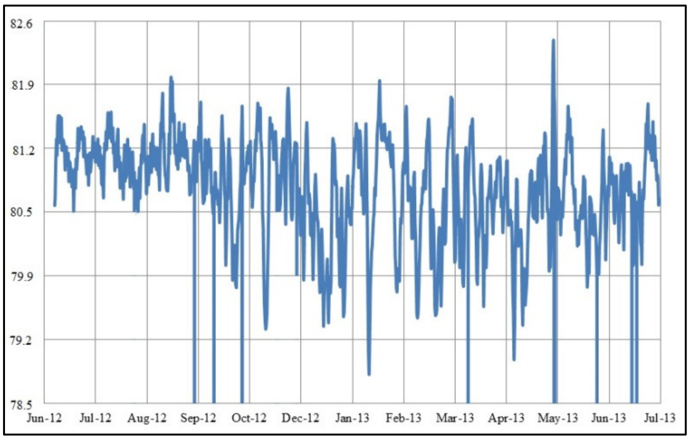

Figure 2. Barometric Pressure in the course of a year kPa.

3 BAROMETRIC PRESSURE AND TEMPERATURE FLUCTUATIONS

Barometric pressure fluctuations may have a significant effect on ventilation conditions. In order to determine the scale of the changes and their behavior, the barometric pressure and temperature was recorded over a one year timeframe.

The mine is located in the high desert with hot summer and low winter temperature climaxes. The maximum temperature was 36ºC in July and minimum -32ºC in January. The average daily temperature fluctuations are over 20ºC, which are larger in summer time with cold nights and hot days.

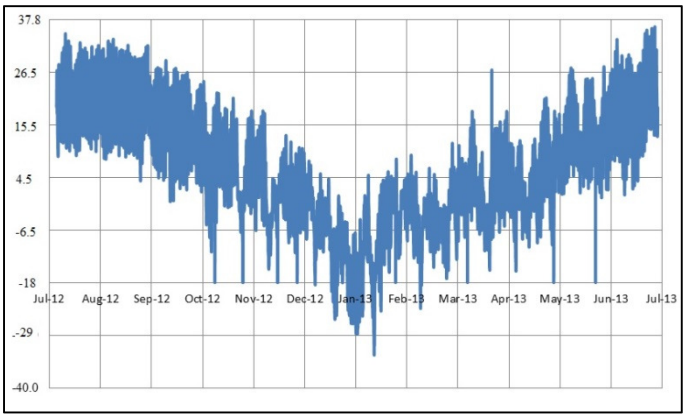

Figure 3. Temperature Readings in the course of a year - degrees C.

3.1 *Daily Pressure and Temperature fluctuations*

To investigate short term fluctuations, the barometric pressure and temperature were monitored for a week during the summer. Figure 4 shows the surface temperature and barometric pressure fluctuations of 25 ℃ and 0.3 kPa respectively during this time.

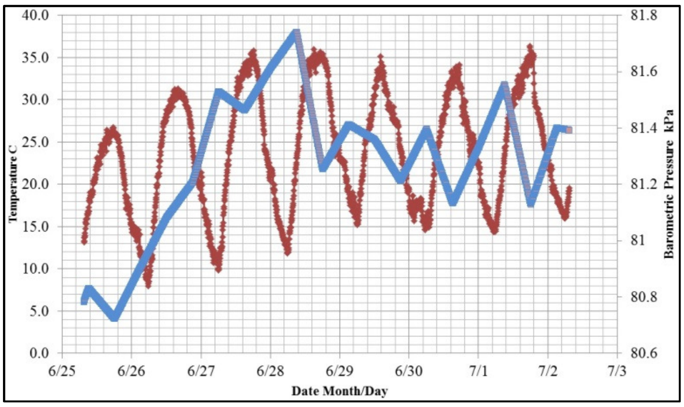

Figure 4. Pressure and temperature readings during a summer week.

4 UNDERGROUND PRESSURE MEASUREMENT

Precise measuring instruments were used to conduct the pressure quantity survey. Paroscientific pressure transducers with an accuracy of 8 Pa allowed precise continuous monitoring during the survey. Digital psychrometers were used to measure dry and wet bulb temperature, relative humidity and dew points. These parameters were then used to calculate the local air density.

4.1 *Cage movements*

A study was conducted during summer, to investigate the effect of cage movements at 8 Shaft which mainly is used for material and manpower transportation along with intake airflow, and consisted of monitoring the absolute pressure at the top and bottom of 8 Shaft, temperature and hoisting activity. Current readings of the surface fans were also monitored.

4.1.1 *Pressure fluctuations*

The pressure readings at the shaft top and bottom were compared against the hoisting log shown in Table 1.

Figure 5 shows the pressure reading on the top of 8 Shaft. The differential pressure in between the top and the bottom of 8 Shaft is shown in Figure 7. Data analysis showed that a pressure differential of 100 Pa to 120 Pa resulted from cage movements.

The psychrometric data were monitored at the bottom of 8 Shaft. The dry and wet bulb temperature increased as the temperature rose on the surface. The relative humidity dropped significantly from 45% at the beginning of the survey down to 27% at the end.

Table 1. 8 Shaft hoisting activity log.

Direction	Start	End	Comments
Down	8:33:00 AM	8:35:00 AM	
Up	8:35:00 AM	8:38:00 AM	
Down	8:46:00 AM	8:49:00 AM	
Up	8:53:00 AM	8:55:20 AM	
Down	8:59:20 AM	9:02:20 AM	
Up	9:04:20 AM	9:07:00 AM	
Down	9:22:45 AM	9:25:40 AM	
Up	9:26:20 AM		30 m
Down	9:41:30 AM		Bottom
Up	9:42:00 AM	9:45:00 AM	
Down	10:35:00 AM	10:37:30 AM	
Up	10:39:00 AM	10:41:20 AM	
Down	10:42:30 AM	10:45:30 AM	
Up	10:46:00 AM		30 m up
Down	10:52:00 AM		Bottom
Up	11:53:50 AM	11:56:40 AM	
Down	12:45:20 PM	12:48:20 PM	
Up	12:51:30	12:54:20	

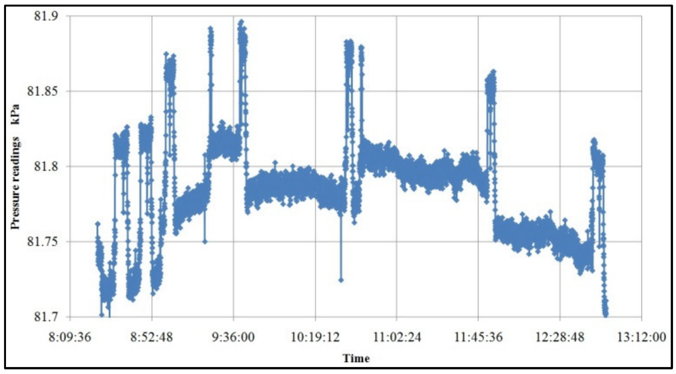

Figure 5. Pressure reading: top of 8 Shaft - kPa.

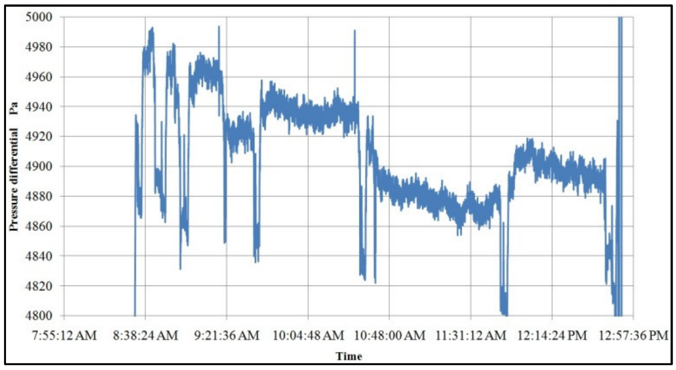

Figure 6. Pressure differential: top and bottom of 8 Shaft - Pa.

Current readings were recorded during the survey and are shown in Figure 7 for 8 Shaft main fan. The surface fans are 175 kW. The graph shows that the motor draws more current as a result of additional resistance in the shaft due to cage movements. It was also determined that keeping the cage at the bottom of the shaft increases the current readings by 5 to 10 A.

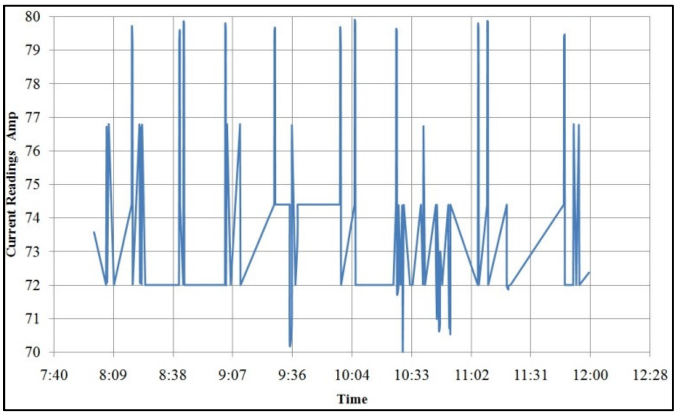

Figure 7. 8 Shaft current readings (amps)

4.2 *Longwall pressure readings*

Psychrometric and pressure readings were taken to investigate the effect of fluctuations at the LW face. A pressure transducer was placed on surface while the second unit was taken underground where pressure was logged every second during travel to the longwall face, stationary, and back to the surface. Figure 8 and Figure 9 show the surface and underground pressure readings during this time.

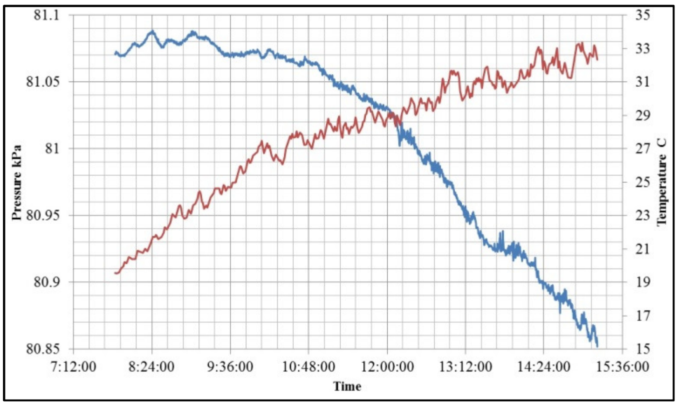

Figure 8. Surface pressure and temperature readings.

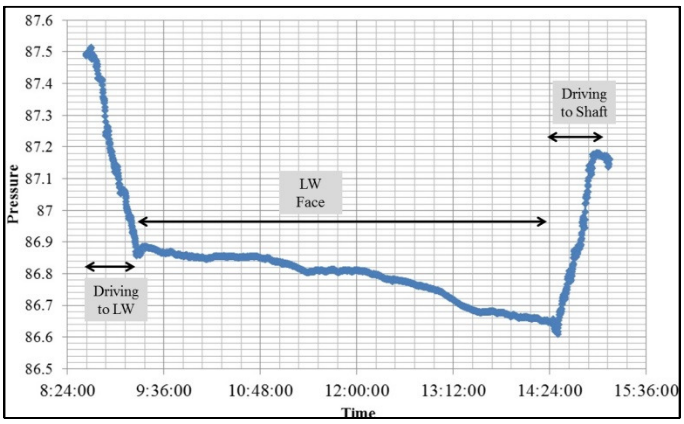

Figure 9. LW face pressure readings, kPa.

As the surface barometric pressure dropped the pressure at LW face decreased. The temperature at LW face was measured 27 ˚C ± 2 ˚C. No correlation was observed between the surface and underground temperature due to the long distance between the intake shafts and strata heat.

4.3 *Stoppage of all main fans*

The natural ventilation pressure and compressibility of the air were taken into account utilizing the ventilation network program Ventsim. A simulation was conducted for a case where all the surface fans were off. The results were compared against experimental (flow direction) measurements that were taken during a mine-idle shift with fans off with good success. The simulation and experimental data are shown in Table 2. The surface dry bulb temperature was 4.4 ˚C for both simulation and experiment.

Table 2, Experimental and simulation results, all fans off.

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

4.4 *Fan Power*

Three identical surface fans force roughly 500m^3/s of fresh air into the mine. The fans are located on top of 5, 7 and 8 Shafts (Figure 1). Number 7 Shaft fan, which is used to ventilate the sumps and pump stations in non-production areas to the north is set to a lower blade setting compared to the other shaft fans. Number 5 and 8 Shaft fans ventilate the major operating sections located in the southern portion of the mine. Number 8 Shaft fan is one blade setting lower than 5 Shaft to increase the efficiency of both.

In January 2013 the blade setting on 7 Shaft was lowered by two blade settings to improve the efficiency. Later, the 8 Shaft blade setting was lowered one setting to reduce leakage in the system as well as pressure operating against 5 Shaft fan. Blade setting reductions resulted in a significant drop in pressure, operating cost, bearing vibration, leakage and natural gas consumption used to heat mine intake air. Number 8 Shaft air is 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 systems would again reduce the pressure and consequently the operating costs. Number 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 (Habibi et al, 2013). Amperage readings were recorded on all three surface fans.

Analysis showed after blade reduction that the annual operating costs dropped by 18 %. Meanwhile, the air quantities were either similar or improved with the overall air efficiency improved by 12 % while maintaining or improving face airflow. Also as a result of the lower fan operating pressure, the pressures across the main stopping lines were also reduced, resulting in less stopping leakage. Airflow reduction in 7 Shaft and 8 Shaft decreased natural gas consumption by 13 %.

Figure 10 shows that the amperage readings on surface fans. 5 and 8 Shafts were running at almost the same range. It was determined that the power consumption is reduced during the summer as air density tends to be lower due to higher temperatures. The average barometric pressure was also determined to be higher in winter. The positive NVP which works in favor of the fans also aids airflow resulting in less current.

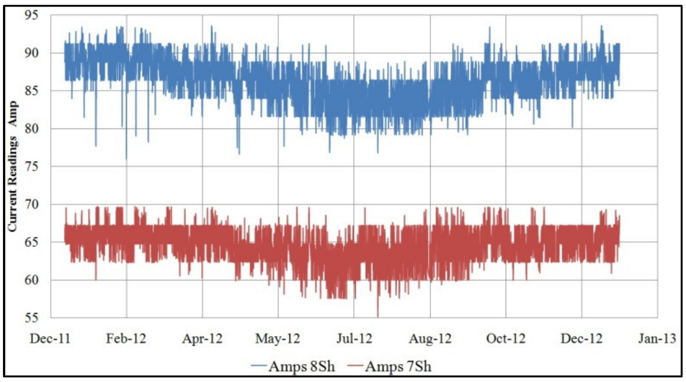

Figure 10. Current reading on surface fans in a course of a year.

5 NATURAL VENTILATION PRESSURE

There are two forces that supply energy to the mine ventilation system: natural and mechanical. Natural ventilation depends on the differences in elevation and air temperature of the surface and the mine workings (Hartman, 1997). The surface temperature variation between summer and winter extremes at FMC trona mine is 45ºC. The mine temperature does not vary significantly, except in intake shafts and locations near the shaft bottom. The effect of diurnal and seasonal changes tends to damp out by the strata which supplies heat to or extracts heat from the ventilating air (Hartman, 1997). If the surface temperature changes from being less than the mine level temperature to above the direction of airflow will also reverse.

The presence of natural draft in mechanically ventilated underground mines is not uncommon. Such natural draft pressures, however, often confuse and complicate the final reduction and interpretation of total pressure data collected during a ventilation pressure survey (Bruce, 1982). The NVP is calculated by measuring the psychrometric properties at the top and bottom of each shaft. Calculation of the NVP is achieved by measuring the barometric pressure and computing the specific volume at the top and bottom of each shaft (Loomis, 1993).

5.1 *Network ventilation model*

There are two general approaches as to how the verification of the network ventilation model can be established. The first is to physically measure all individual branches and then calculate their resistance factors for input into the software. In the second approach, the network is assembled using estimated Atkinson K factors (Von Glehn, 2008). For the purpose of this study a comprehensive pressure quantity survey (using pressure transducers) was conducted to measure all the individual branch resistances. To assist in the quantification of natural ventilation energies and the fan operating point, dry bulb temperature, relative humidity and barometric pressure were also measured (Prosser et al, 2002). The results are highly affected by density. The flow and pressure distribution throughout the mine become significantly different if density change is accounted for or is neglected (Partyka, 1991).

5.2 *Discussion and results*

The NVP calculations were conducted using both Indicator Diagram (the density difference between the columns) and thermodynamic approach methods.

5.2.1 *Indicator diagram*

Using equation 1 and 2 the specific volume and the index of polytropic process n between top of intake shaft and return shaft was calculated.

$$\vartheta = \frac{RT}{p} \tag{1}$$

where ϑ is specific gravity (m^3/kg), R is the gas constant (J/kmol.K), T is the temperature (K) and p is pressure (kPa).

$$n = \frac{1}{1 - \frac{\ln(\frac{T_2}{T_1})}{\ln(\frac{p_2}{p_1})}} \tag{2}$$

Table 3 shows the results for the selected circuit during fall when the surface temperature was approximately 8 ºC. The elevation and temperature have been accounted for in density calculations. The results also were compared with Ventsim simulations.

Table 3, 8 Shaft cage activity, input values for PV diagram.

#	Location	Pressure kPa	Specific Volume m^3/kg	n
1	Fan inlet	79.89	1.051	1.765
2	Top intake shaft	81.65	1.038	1.184
3	Bottom intake shaft	85.98	0.994	0.744
4	Bottom return shaft	84.96	1.010	1.096
5	Top return shaft	79.89	1.068	0.000
1	Fan inlet	79.89	1.051	1.765

The indicator diagram was used to calculate the Natural Ventilation Energy (NVE) and fan work. The calculated NVE was 136 J/kg and fan work 1855 J/kg. Thus the NVP was calculated to be 132 Pa using the local density of 0.963 kg/m^3, Figure 11 shows the PV diagram.

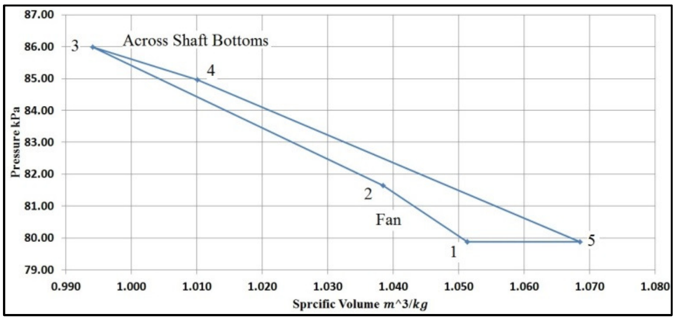

Figure 11. P ϑ diagram.

5.2.2 *Thermodynamic approach*

The reduced energy balance equation; Equation 3 was used to calculate the frictional energy losses in the intake shaft, workings and the return shaft. The mechanical energy supplied to the air to overcome this frictional energy loss was the flow work done by the fan calculated using Equation 3.

$$(Z_1 - Z_2) = \int_{p_1}^{p_2} \vartheta \, d_p + H_{l_{12}} \quad (3)$$

The fan flow work was calculated to be 1840 J/kg where total energy loss was calculated to be 2008 J/kg using equation 4.

$$\dot{W}_{12} = \int_1^2 \vartheta - d_p + H_l = h_2 - h_1 \quad (4)$$

where h is enthalpy (J/kg). Therefore, the natural ventilation energy was 168 J/kg. The correspondent natural ventilation pressure at fan intake was calculated to be 162 Pa. The polytropic efficiency of the fan was calculated as 65% using useful fan output and input to fan $\dot{W}_{12}$. The mass flow of air in the system at 8 Shaft was calculated to be 196 kg/h using the total air quantity at the inlet. Thus the Natural Ventilation Power can be calculated to be 33 kW.

The results for calculated natural ventilation pressure from both methods are 18% apart. The positive NVP may be considered as the discrepancy between the fan flow work and total work is -168 J/kg. The negative value shows that the fan is doing less work to overcome the system resistance.

6 CONCLUSIONS

A pressure and quantity survey was conducted at FMC's Westvaco trona mine to generate the ventilation model which was then utilized to improve the system by adjusting the surface fan blade settings and to run various simulations such as heat and NVP simulations. The barometric pressure along with psychrometric properties were recorded over a one year period and results compared against underground pressure readings to investigate the effect of surface pressure fluctuations on the ventilation system. The surface main fan current readings were measured to determine the effect of changing barometric pressure on energy consumption. The effect of cage movement was investigated by monitoring the pressure drop in the shaft and fan current readings. The NVP was also calculated for a closed loop from top of the intake shaft to the top of the bleeder shaft.

Following is a review of the results and observations:

- The main fan blade settings were lowered at 7 and 8 Shaft, significantly improving the fan efficiency, reducing energy consumption by 18 %. The overall ventilation efficiency of the network increased by 12 %, improving airflow to mining areas.
- A natural ventilation pressure simulation was done comparing airflow directions against the experiment performed with all the surface fans off. Results show that the NVPs could have adverse effects on mine airflow directions (if the fans are off). The reversed airflow could create unexpected conditions at the mining face.
- The barometric pressure readings were monitored over the course of a year along with surface temperature fluctuations. It was determined that the average daily temperature fluctuations are approximately 20°C and are larger in summer. Barometric pressure readings were steadier in summer where large fluctuations were measured in winter. The fan energy consumption was less during summer.
- The pressure at the top and bottom of 8 Shaft and fan current readings were monitored while the cage was operated in both directions. A pressure drop of 100 Pa was measured while the cage was travelling down (with airflow) and slightly higher when the cage was moving upward. The fan current

readings would peak (20 amps over) and then settle once (5 to 10 amps over) the cage moved in either direction. Fan pressure and current readings increase if the cage is kept at the bottom of the shaft in comparison to the top of the shaft.

- The NVP was calculated using the Indicator Diagram and thermodynamic approach. At the time of the test, the positive natural ventilation pressure of approximately 132 to 160 Pa corresponded to 33kW of ventilation power. This means NVP assists the fan improving mine airflow and reducing power. The magnitude of the NVP is the function of temperature, barometric pressure and fan pressure.

7 ACKNOWLEDGMENT

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