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A FIELD EVALUATION OF A MAIN AXIAL VENTILATION FAN TO ESTABLISH STALL ZONE AND FAN PERFORMANCE CURVE

Tim Harvey¹ and Bharath Belle²

ABSTRACT: This paper summarises the approach taken in establishing and validating the stall zone of a main axial fan for an underground expansion project. The expansion of an operating underground bord and pillar mine required the use of a second fan in parallel at the start of the development project. To improve the level of confidence in the ventilation simulation model that incorporated an existing fan curve provided by the fan supplier necessitated an independent fan test. Therefore, performance and stall characteristics of the current fan and pressure-quantity (PQ) survey of the mine was conducted and the results were used to calibrate the ventilation simulation model. The main axial fan was tested through a range of operating points beyond the currently perceived pressure stall point of 2.1 kPa. A pitot traverse was conducted for two operating points and the remaining operating points were measured on fan instruments. This paper details the test procedures and instruments used to collect and analyse data, and the theory used in analysis and to calibrate fan differential pressure flow measurement instruments. The fan test study has validated the fan curves with different pitch setting for use in ventilation simulation studies with twin fan installations operating with the fan pitch set to 17.5º, which is to give a good operating safety margin from the stall zone of 2.6 kPa.

INTRODUCTION

Main ventilation fan is a key safety and business critical control for underground risk management. One of the key requirement of mine fans is that they are robust, reliable and have the flexibility to provide required pressure and air quantities to the mine design requirements. Unintended fan performance would result in ventilation conditions that may create hazards such as elevated levels of hazardous gases, pollutants, stoppages of working places and evacuation of workers from the underground environment (MDG3 2015). Current or new mine projects seek to utilise the existing mine or spare main fans from an operating mine. This paper summarises the evaluation of one such axial fan used in the pre-feasibility expansion study of a care and maintenance bord and pillar mine. The work was carried out by identifying the stall zone of an existing axial main fan installation that was used in a ventilation simulation model.

This axial fan (400 kW) installation is understood to be capable of operating at up to a pressure of 2300 Pa (at 20º fan blade setting). However, during the simulation studies, it was noted that there was uncertainty about the axial fan performance curve the operating mine had been using. In addition, it was established that the original fan manufacturer did have model test curves for the current axial fan at 20º pitch but the test results for 15º and 25º blade pitch could not be found. A review of ventilation simulation models indicated that they were highly conservative but the project needed more certainty on the main fan performance curve and the stall zone prior to installing a similar second axial fan when introducing a second continuous miner for development. This paper documents the results of the main fan and mine Pressure Quantity (PQ) survey that ascertained the axial fan performance curve and the stall zone and validity of the mine resistance used in ventilation modelling.

BACKGROUND

The fan evaluation work discussed in this paper was carried out at a bord and pillar mine (2 m seam height) with a single Continuous Miner (CM) development. The mine ventilation system consisted of two

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intakes (conveyor, travel) entering from the highwall drawing 110 m$^3$/s using an exhaust fan operating at a pressure of 800Pa (Figure 1).

The main ventilation fan at the mine is an axial flow fan, rated at 75 m$^3$/s at 2,000 Pa and the exhaust fan was operated mostly on the lower pressure part of the fan curve. The return exhaust duct is equipped with dual ducts to accept a second large fan but was fitted with a 45 kW fan instead. However, the mine has operated with only minimal contingency (spare motor) against a fan failure and an adequate backup fan capacity for emergencies. The main fan infrastructure and fan operating point for single fan is shown below (Figure 2) and was not able to provide sufficient capacity for the second CM unit as part of the LW expansion project.

The objective of an independent fan testing was to correlate actual performance to manufacturer’s curves, understand pitch settings of fans, identify the location of stall zone and behaviour of fan in suspected stall zone and enable the selection of operating pitch for twin axial fans in parallel operation. The supplier fan curve were produced from a 1.0 m model fan with an inline fan duct system.

A fan test at current pitch ($14^\circ$) was undertaken to produce fan Pressure-Quantity (PQ); power-quantity curves and to determine the location of the axial fan stall point. An underground PQ survey was conducted to get improved better friction and resistance values for the existing bord and pillar mine and to use these in the simulation model to determine a better estimate of mine resistance. Using this information, the adequacy of the proposed twin fans to meet the required ventilation quantities with a safe margin on stall could then be evaluated and the optimum pitch setting for the fans selected. The current mine resistance determined during a ventilation survey was 0.0669 N.s$^2$/m$^8$. The axial fan test was conducted over three days by a brattice regulator (with a mesh, and Acro-Prop) set-up using the frame of the 70 kPa mine seal in 5 heading outbye of single exhaust airway (Figure 3). The fan was evaluated with ~6 m$^2$ opening at regulator by a pitot traverse at a series of different mine resistances. The regulator orifice sizes were varied to the following predetermined openings, fully closed, 1, 1.2, 1.5, 2, 3, 4, 5, 6, 7 and 8 m$^2$ openings. Measurements were done using the fan Citect instruments in parallel with...
Paroscientific barometers and power was measured and logged using the Mines Fluke1375 Power Logger. A separate fan test was carried out at a 4 m² opening at the regulator by a second pitot traverse.

![Figure 3: Location of Brattice regulator for fan stall zone testing](image)

**MAIN FAN EVALUATION PROCEDURE**

The following procedure was followed prior to the main fan testing and the general test principles can be used when evaluating any other such fans:

- Loosen the bungs on both side of duct at measuring station to enable holding tool for long pitot tube during fan test.
- Construct a substantial prop and mesh stopping frame in main return just outbye of one cut-through probably braced against the 70 kPa seal door frame and seal the spare fan outlet and Y piece explosion panels to reduce leakage.
- Check fan instruments for accuracy and inspect tubing for potential leaks and blockages (test individual static tubes), fan instruments have valves on T piece so check readings can be made while Citect is recording readings.
- Check temperature and vibration transducers and current and voltage Citect readings using clip-on current meter and voltage meter.
- The inside duct, fan blades straightening vein and inlet screen and duct should be cleaned prior to testing.
- Determining fan pitch requires the fan to be stopped and isolated electrically by removing the access cover on the upper platform. The pitch setting on each blade can be determined by measuring in the plane of rotation the distance from the leading edge and the trailing edge of the blade tip from a fixed point.
- All resistance points should have check readings with barometers paralleled with fan pressure instruments.
- Duct DBT and WBT readings should be taken every 30 minutes and atmospheric pressure recorded frequently (at least each time the pitot tube is moved to a different traverse plane).
- Each pitot tube measuring point should be recorded for at least 30 seconds (barometers logging ~ 1 sec, and average data); other points checked including those in stall should be read over ~ 5 minute period noting the accurate time of each reading is essential for later data analysis and photos of each test point orifice regulator hole would help complete the work.
- The stall location will require greater attention to listening to the noise variations and barometers by testing well beyond stall to confirm performance in this region.
- Each fan test duty point test instrument is checked with barometers.
- When using barometers it is important to know the instrument height (RL) (and when tubes connected to instrument the height of the tube inlet) also air density (calculated from abs pressure, WBT and DBT) at instrument and at tube inlet.
- When doing pitot traverses one instrument is used for measuring atmospheric pressure and the other is used to measure static and velocity probe readings. Data logged and time scale on instruments and Citect needs to be the same.
• Both instruments are placed at the same level and the difference between the two pressures plus height correction for the probe ~ from 15 to 45 Pa are made to readings to get pressure values.
• For underground surveys an instrument is left at a known height on the surface, it could be left on the surface outside the control room (non-air-conditioned) at that location WBT and DBT readings are taken.
• The second instrument is taken underground and a synchronised watch is required to record the timing of each reading WB and DB and RL of location required for each reading (if tube is used through a stopping then RL of instrument and tube inlet are required and the WBT/DBT at instrument and tube entry. WBT and DBT readings are taken both inside and outside the duct ~ every 30 minutes for density calculations.
• The instruments should be set up to record an average reading every second and left at each measuring point for at least 1 minute. Data is then averaged for the measuring period.

Figure 4 shows the effect on mine resistance for regulator open area which indicates that the potential stall of the fan at about 1.2 m$^2$ open area. The tests were done using a full traverse with pitot tube at current operating point, ~ 4 m$^2$ Mine resistance and ~ 2 m$^2$ mine resistance point on curve. These positions were expected to provide good control on curve and enable fan instrument calibration to be checked as different flows. The rest of points on curve can be obtained from fan instruments. Barometers were set up in parallel with them to confirm readings. Each of these readings will only take 5 minutes once pressure and flow have stabilised after regulator changes. It is important that stable conditions exist while each set of readings is being taken by ensuring no vehicle movement or opening/closing of man doors and regulator brattice is not flapping.

![Figure 4: Effect on mine resistance of fan test regulator openings](image.png)

Pitot grid has 25 points and the probe can reach the middle 3 points from one side and the two outside points are more easily measured with a shorter probe (the long probe is 96”). The fan pressure transducers have a test instrument connection and the barometer is connected to check measurements.

**Test Instrumentation**

Data was collected for various regulator settings from fully closed to an 8 m$^2$ opening using the following instruments:

• The fan instrument (2 X Emerson 3051S1CD Differential Pressure (DP) transmitters one Ranged 0 to 1000 Pa for DP (flow readings) and the other ranged 0 to 3000 Pa for static pressure (at inlet to inlet box)) data from Citect (5 second average data for flow and static pressure).

• Barometer data (one reading atmospheric pressure and the other absolute pressure (alternatively) from each of the fan instrument static rings.
- Wet Bulb Temperature (WBT) and Dry Bulb Temperature (DBT) readings from inside and outside fan duct.
- Fan shaft power from Fluke1375 Power logger, power data and fan motor efficiency at percentage load data from motor supplier information.
- The two ParoScientific barometers (in working condition and charged)
- A Comark of other DP pressure transducer (if available)
- Quality thermometers for WB, DB readings
- The 3.0 m and 1.5m pitot tubes and tubing
- Electrical equipment to monitor motor current, volts and power factor.
- A platform ladder to do pitot traverse.

Pitot traverse

The pitot traverses were conducted on the measuring plane inbye of the inlet to the fan inlet box. Data from the traverse was compared to fan instrument readings from real-time monitor-Citect. Fan instrument readings were checked on barometers connected in parallel with fan instruments (Figure 5 and Figure 6). For pitot traverses, both barometers are placed at the same elevation, one reading atmospherics pressure and the other read the absolute pressure at the pitot tube, static or total, depending on the position of the three-way-valve connecting tubes to the barometer. As both barometers are at the same elevation there is no need to correct differential pressure readings for height differences (although the height effect is taken into account for absolute pressures in density calculations). The pressure reading is simply the difference between the two barometer readings (if there is no zero correction between barometers). The barometer time clocks were synchronised with Citect time and were set to log data every second. Because of a slight difference in logging between barometers (occasional lost data points), “Vlookup” statements are used to synchronise data and to relate 5 second Citect data to barometer readings. Figure 5 shows fan pressure quantity and test instrumentation and measuring planes.

Figure 5: Fan instrument location and pitot traverse plane and tube ports in duct

Figure 7 shows sample data from three point measurements of static and total pressures, in transitioning between points the pitot tube is rotated ~90° to the flow, this is to give a spike in data to help in differentiating between data points. The average data from ~ 15 seconds at each point is selected manually from graphs and subtracted from the average atmospheric barometer readings, for the same time period, to produce data for flow calculations.
Table 1 shows the pressure data and flow calculation for the latest pitot tests and an historic test when fan pitch was ~ 21°. At the bottom of tables the average Citect Static Pressure readings from the fan inlet box entry (~ 1 m upstream of the pitot traverse plane on upstream side of the Fan Dampers), the barometer check of these readings and the calculated Citect Flow readings (averaged over the test period). The closeness of these readings (within 2% on pressure and less than 0.5% on flow) shows that fan instruments and Citect readings are within the accuracy range of this type or instrumentation.
### Table 1: Summary of pitot traverse results

| Point | SP Static Pressure (Pa) | TP Total Pressure (Pa) | VP = SP - TP | VELOCITY VELOCITY QUANTITY | AVERAGE Duct Density (kg/m³) | Duct dimensions at measuring plane (190mm upstream of holes): Height m and Width m | Area A m² | VP = √(2 * ρ * Q / ρ) * 0.5 | Q = v * A | FSP m³/s | TP Calc | Avg SP-VP Calc | Average Flow From Citect | Barometer | Average Flow From Barometer |
|-------|-------------------------|------------------------|---------------|---------------------------|----------------------------|--------------------------------|-----------------|--------------------------------|-----------------|----------------|------------------|-------------------------|----------------|--------------------------|
| 1.1   | 735.5                   | 595.9                  | 139.6         | 15.6                      | 1.1301                     | 1.131 kg/m³; 2.2116 m and 3.164 m and 6.9974 m²; Duct dimensions at measuring plane | 6.9974 |                                |                 |                 |                  |                          |                |                          |
| 1.2   | 731.6                   | 628.1                  | 103.5         | 13.4                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 1.3   | 722.4                   | 605.1                  | 117.3         | 14.3                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 1.4   | 712.4                   | 605.9                  | 106.6         | 13.6                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 1.5   | 705.7                   | 612.7                  | 93.1          | 12.7                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 2.1   | 733.3                   | 602.3                  | 131.0         | 15.1                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 2.2   | 728.2                   | 598.9                  | 129.4         | 15.0                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 2.3   | 738.3                   | 588.1                  | 150.2         | 16.2                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 2.4   | 718.5                   | 603.3                  | 115.2         | 14.2                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 2.5   | 727.7                   | 623.9                  | 98.8          | 13.1                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 3.1   | 736.1                   | 594.9                  | 141.2         | 15.7                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 3.2   | 746.4                   | 605.8                  | 140.6         | 15.6                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 3.3   | 734.7                   | 590.1                  | 144.6         | 15.9                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 3.4   | 729.8                   | 601.6                  | 128.2         | 14.9                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 3.5   | 726.5                   | 646.4                  | 80.2          | 11.8                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 4.1   | 734.8                   | 600.1                  | 134.7         | 15.3                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 4.2   | 744.6                   | 604.7                  | 140.0         | 15.6                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 4.3   | 743.5                   | 601.7                  | 141.8         | 15.7                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 4.4   | 729.6                   | 605.3                  | 124.3         | 14.7                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 4.5   | 728.4                   | 620.9                  | 107.5         | 13.7                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 5.1   | 735.3                   | 606.8                  | 128.5         | 15.0                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 5.2   | 741.9                   | 611.1                  | 130.7         | 15.1                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 5.3   | 739.9                   | 609.8                  | 130.1         | 15.0                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 5.4   | 739.4                   | 604.9                  | 134.5         | 15.3                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| 5.5   | 730.3                   | 615.3                  | 115.0         | 14.1                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
|       |                         |                        |               |                           |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| Average | 731.6                  | 607.3                  | 124.3         | 14.7                      | 102.62                     | 121.5                          | 610.1 |                                |                 |                 |                  |                          |                |                          |
| Citect | 784.7                  | C                      | 0.577         | F                         | 103.57                     | Average Flow From Citect       |                |                                |                 |                 |                  |                          |                |                          |
| Barometer | 787.3                  | K                      | 0.985         | 4.86                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| Summary Results from Pitot traverse results from 26th March 2014 | 1,194.6               | 1,085.5               | 109.2                | 13.67                  | 95.63                      | 106.8                          | 1087.8 |                                |                 |                 |                  |                          |                |                          |
| Citect | 1237.0                  | C                      | 0.574         | F                         | 96.78                      | Average Flow From Citect       |                |                                |                 |                 |                  |                          |                |                          |
| Barometer | 1232.2                  | K                      | 0.950         | 4.85                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |
| Summary Results from Pitot traverse results from 17th May 2007 | 1,454.6               | 1,270.2               | 184.4                | 17.7                    | 123.94                     | 179.6                          | 1275.0 |                                |                 |                 |                  |                          |                |                          |
| Citect | 1583.0                  | C                      | 0.573         | F                         | 119.86                     | Average Flow From Citect       |                |                                |                 |                 |                  |                          |                |                          |
| Barometer | 1584.6                  | K                      | 0.662         | 5.06                      |                            |                                |                  |                                |                 |                 |                  |                          |                |                          |

Average duct density, ρ, 1.131 kg/m³; Duct dimensions at measuring plane (190mm upstream of holes): Height-2.2116 m and Width-3.164 m and Area -6.9974 m²; *summary results from second pitot traverse; ** summary results from historic pitot traverse.

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**DATA ANALYSIS PROCESS FROM PITOT TUBE TRAVERSE DATA**

Data reduction is partly done using part of the method from AS ISO 5801-2004, Section 27 “Determination of flowrate using a Pitot-static tube traverse” using the formulas from 27.5 for mass flow and expansibility factor, and data from 27.6 below for the flow rate coefficient. The Isentropic Exponent K and density are calculated using ASHREA software “Ashrae LibHuAirPRop” from absolute pressures, WBT and DBT in the duct. The calculation for density from Section 27 using the static temperature method produced exactly the same density as ASHRAE software. The static temperature is calculated to within 0.1º of duct DBT. Given the accuracy of thermometers used during tests, the duct DBT was used in lieu of static temperature in all calculations.

\[
\Delta P_m = \left[ \frac{1}{n} \sum_{j=1}^{n} \Delta P_j^{0.5} \right]^2
\]  

(1)
where

\[ \Delta P_m = \text{Average Differential pressure on measuring plane in Pa} \]

\[ n = \text{Number of points and } j = \text{the identifier for and individual point} \]

\[ Q_m = \alpha \cdot \varepsilon \cdot A \cdot \sqrt{2} \cdot \rho_x \cdot \Delta P_m \] (Mass Flow) kg/s (2)

And

\[ Q = Q_m \cdot \rho_x \] (Flow) m³/s

where

\[ \rho_x = \text{Density at measuring plane} \]

\[ A = \text{Crosssectional Area of measuring plane} \]

\[ \varepsilon = \left[ 1 - \frac{1}{2K} \cdot \frac{\Delta P_m}{\rho_x} + \frac{(K+1)}{6K^2} \cdot \left( \frac{\Delta P_m}{\rho_x} \right)^2 \right]^{0.5} \] (Expansibility factor) (3)

\[ \alpha \] is estimated from the Reynolds Number \((Re_x)\) at the Section and the equation below fitted to data tabulated in section 27.6 of AS ISO 5801-2004 a polynomial fitted to this data was used in calculations.

\[ Re_x = \frac{\rho_x v_x D_h x}{\mu_x} \] (Reynolds at measuring plane) (4)

\[ \alpha = A + B \cdot \exp(C \cdot Re_x) + D \cdot \exp(E \cdot Re_x) \] (Flowrate coefficient) (5)

Where

\[ A = 9.92452178341E - 01, B = -5.16985037262E - 03, C = -9.69497112333E - 06 \]

\[ D = -2.63697519572E - 03 \text{ and } E = -5.88269194907E - 07 \]

\[ v_x = \text{Average Velocity at measuring plane (m/s)} \]

\[ D_h x = \text{Hydraulic Diameter at measuring plane (m)} \]

\[ \mu_x = \text{Viscosity of fluid at measuring plane (Pa .s)} \]

The pitot travers data was used to calculate flow and Fan Static Pressure (FSP) and motor shaft power at each regulator setting, and the results were standardised to density of 1.2 kg/m³ for use in ventilation simulation models. The pressure, quantity, kW, and efficiency curves for 14º fan pitch in Table 3 and Figure 10 were derived from the test data in Table 2 and Table 3. Figure 8 and Figure 9 show the barometer data using differential pressure rings during fan tests and snapshot of the data for a test regulator area respectively.

### Table 2: Test results for various regulator openings

<table>
<thead>
<tr>
<th>Regulator open area, m²</th>
<th>From Fan Instrument-Citect</th>
<th>From Barometers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow, m³/s</td>
<td>Static, Pa</td>
</tr>
<tr>
<td>-------------------------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>0</td>
<td>38.5</td>
<td>2491</td>
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<tr>
<td>1</td>
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<td>3</td>
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<tr>
<td>5</td>
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<tr>
<td>8</td>
<td>101.5</td>
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Table 3: Fan performance curves for ventilation models at density of 1.2kg/m³

<table>
<thead>
<tr>
<th>Flow m³/s</th>
<th>FSP Pa</th>
<th>Shaft kW</th>
<th>Flow m³/s</th>
<th>FSP Pa</th>
<th>Shaft kW</th>
<th>Flow m³/s</th>
<th>FSP Pa</th>
<th>Shaft kW</th>
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<td>86.5</td>
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<td>2377.1</td>
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<td>94.4</td>
<td>2368.6</td>
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<td>90</td>
<td>2092.3</td>
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<td>95</td>
<td>1995.1</td>
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<td>90</td>
<td></td>
<td>1628.6</td>
<td>105</td>
<td>1609.1</td>
<td>256.3</td>
<td>Unstable Flow (Stall-suspected)</td>
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<td></td>
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<tr>
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<td></td>
<td>973.8</td>
<td>110</td>
<td>1260.1</td>
<td>244.5</td>
<td>Minor Flow instability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>108</td>
<td></td>
<td>134.9</td>
<td>118</td>
<td>565.9</td>
<td>216.4</td>
<td>Maximum Operating Pressure</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 8: Barometer data from fan test using fan differential pressure rings

Figure 9: Example of data selection method from fan instrument data for 4m² opening
The velocity profile across the duct using data from Table 2 is shown in Figure 11.

**CALCULATION OF FLOW FROM FAN INSTRUMENT DIFFERENTIAL PRESSURE READINGS**

The origin of differential pressure flow measurements is described below. The Bernoulli equation represents energy conservation for a fluid element:

\[
\text{Const} = \rho \cdot g \cdot h + \frac{\rho}{2} \cdot v^2 + P
\]  

(6)

Where

- \( \rho \) = Fluid Density \( \text{kg/m}^3 \)
- \( v \) = Linear velocity of the fluid element \( \text{m/s} \)
- \( P \) = Pressure in Pa

The first term \( \rho \cdot g \cdot h \) is the potential energy coming from height on the gravitational field. For this specific evaluation, constant height of exhaust airflow is assumed, so the equation is re-written to:

\[
\text{Const} = \frac{\rho}{2} \cdot v^2 + P
\]  

(7)

The term \( \frac{\rho}{2} \cdot v^2 \) is kinetic energy, here the density replaces mass. The pressure \( P \) can be understood as a potential energy. Work is stored in compressing the fluid the same way as a compressed spring stores energy.

We apply this equation to a circular cross section pipe that is reduced in diameter as it goes downstream in horizontal direction as in Figure 12.

![Figure 12: Flow in Reducing Diameter Pile](image)
\[ \frac{p_1}{2} \cdot v_1^2 + P_1 = \frac{p_2}{2} \cdot v_2^2 + P_2 \]  
(8)

Where the subscripts 1 and 2 represent Upstream and Downstream respectively.

As mass is conserved along the pipe

\[ Q_M = \rho_2 \cdot v_2 \cdot A_2 = \rho_1 \cdot v_1 \cdot A_1 \]  
(9)

Where

\( Q_M \) = Mass Flow in kg/sec

\( A_i \) = Cross sectional area of pipe upstream

\( A_2 \) = Cross sectional area of pipe downstream

Squaring both sides of (4) and solving for \( v_2^2 \) we get

\[ v_2^2 = v_1^2 \cdot \left( \frac{\rho_1 \cdot A_1}{\rho_2 \cdot A_2} \right)^2 \]  
(10)

Rearranging Equation (3)

\[ 2 \cdot (P_1 - P_2) = \rho_2 \cdot v_2^2 - \rho_1 \cdot v_1^2 \]  
And substituting \( v_2^2 \) from equation (5) into this equation we get

\[ 2 \cdot (P_1 - P_2) = v_1^2 \cdot \left( \frac{\rho_1 \cdot A_1}{\rho_2 \cdot A_2} \right)^2 - \rho_1 \]  
\[ = v_1^2 \cdot \frac{(\rho_2 \cdot (\rho_1 \cdot A_1)^2 - \rho_1 \cdot (\rho_2 \cdot A_2)^2)}{(\rho_2 \cdot A_2)^2} \]

Hence \( v_1 \) can be written as

\[ v_1 = \sqrt{2 \cdot (P_1 - P_2)} \cdot \sqrt{\frac{(\rho_2 \cdot A_2)^2}{(\rho_2 \cdot (\rho_1 \cdot A_1)^2 - \rho_1 \cdot (\rho_2 \cdot A_2)^2)}} \]  
(11)

And

\[ Q = v_1 \cdot A_1 \] Quantity in m³/s  
(12)

Derivation of Flow Calculation in Citect

The \( P_1 - P_2 \) (ΔP) in equation 6 above is measured loss between the two static rings and the formula does not allow for shock losses in the inlet Box so the value of \( P_1 - P_2 \) needs to have the inlet box shock loss subtracted from it.

Shock Loss, \( P_s = K \cdot \rho_1 \cdot \frac{v_1^2}{2} \)  
(13)

Where \( K \) = the shock loss factor

By substitution in Formula 6 above (for simplification) let

\[ C = \sqrt{2 \cdot (P_1 - P_2) \cdot \frac{(\rho_2 \cdot A_2)^2}{(\rho_2 \cdot (\rho_1 \cdot A_1)^2 - \rho_1 \cdot (\rho_2 \cdot A_2)^2)}} \]  
Then

\[ v_1 = C \cdot \sqrt{2 \cdot (P_1 - P_2 - K \cdot \rho_1 \cdot \frac{v_1^2}{2})} \]  
Substituting for \( C \) and ΔP in equation

\[ v_1 = C \cdot \sqrt{2 \cdot (P_1 - P_2 - K \cdot \rho_1 \cdot \frac{v_1^2}{2})} \]  
Squaring both sides and multiplying out

\[ v_1^2 = C^2 \cdot 2 \cdot P_1 - C^2 \cdot 2 \cdot P_2 - C^2 \cdot K \cdot \rho_1 \cdot v_1^2 \]  
Rearranging

\[ v_1^2 (1 + C^2 \cdot K \cdot \rho_1) = C^2 \cdot 2 (P_1 - P_2) \]  
Separating \( v_1 \) and taking Square root of both sides results in

\[ v_1 = \sqrt{\left( (P_1 - P_2) \cdot \frac{1}{1 + C^2 \cdot K \cdot \rho_1} \right)} \]  
(14)

In the PLC for Citect Density is assumed to be constant so a fixed Multiplier by \( \sqrt{\Delta \cdot P} \) will give \( Q \)

Citect Differential Pressure Multiplier  \( (F) = \sqrt{2 \cdot A_1 \cdot \sqrt{(C^2) \cdot (1 + C^2 \cdot K \cdot \rho_1)}} \)  
(15)
With $\rho_1 = \rho_2 = 1.15$, $A_1 = 6.974$, $A_2 = 3.65469$ and $K = 1.0$ ($K$ is shock loss factor for inlet box referenced to the inlet box entry area and was derived by calculating the value of $K$ that makes the flow calculated from the differential pressure on fan instruments equal the flow calculated from pitot traverse.

$$F = 4.82$$

As Differential Pressure ($\Delta P$) comes into Citect as a 4 to 20 milliamp signal ranged from 0 to 1000Pa

The milliamp Differential Pressure signal ($mA$) is converted to pressure by the following formula

$$\Delta P = (mA - 4) \cdot \frac{1000}{16} \text{ in Pa}$$

(16)

As the Flow is the Square Root of the Differential Pressure Multiplied by $F$ the formula in Citect uses a Multiplier of

$$F \cdot \sqrt{\frac{1000}{16}} = 38.10545$$

Therefore in Citect $Q \text{ (Flow)} = 38.10545 \cdot \sqrt{(mA - 4)} \text{ in m}^3/\text{s}$

(17)

Unfortunately the densities $\rho_1$ and $\rho_2$ are not equal and as flow increase they become less equal and the accuracy of the Citect calculation reduces. An adjustment could be made in Citect to adjust for density based on static pressure, differential pressure and duct temperature which would improve the accuracy.

The density values can be calculated by the following formula:

$$\rho = \frac{P \cdot M}{R \cdot Z \cdot T \cdot 1000}$$

Density ($\rho$) = Absolute Pressure (kPa) * Molecular Weight / (Z * R * (273.15 + DBT °C))

And as Molecular Weight and Z (Compressibility Coefficient) will not vary much with condition in fan duct a more accurate flow could be calculated.

It should be noted that in data analysis the Citect $\Delta P$ values were back calculated using the Citect Flow by reversing the formula to get the $\Delta P$ i.e. $\Delta P \text{ (Pa)} = (\text{Flow}/4.82)^2$. Unfortunately Citect rounds flows to zero decimal places so the $\Delta P$ values generated are noisier than they should be and accuracy only comes from averaging many values. It would be advisable to report Citect Flow data to 1 decimal place given the accuracy of $\Delta P$ Values (If only to make future back calculations more accurate) or to store the Actual $\Delta P$ values as well as flows.

Note Formula 9 was used to recalculate the fan instrument and barometer differential readings for fan test using a shock loss “K” value of 1 was used to determine flows from differential pressure values (Formula 8). The value of 1 was based on results from pitot tests (Tables 1), however it should be noted that the K value determined by the same method from the pitot test previously gave a K value or 0.655, substantial less than the value of 1 determined during this test. However, no error could be found in the data to cause this difference and instrument values matched. It can be suspected that there is some flow disturbance at the inlet box entry (probably associated with inlet dampers and inlet screen) that was affecting results. It should be noted that the manufacture predicted a loss factor (K) of 0.8 for the inlet box.

As a result of this, the Shock Loss factor (K) was recalculated between the pitot measuring plane and the fan inlet static ring (ignoring the inlet box static ring values) and the agreement between data sets was much closer averaging 1.4 and ranging from 1.364 to 1.44 (Note these new values are relative to the velocity pressure at the pitot measuring plane c.f. previous values that were relative to the velocity pressure at the static ring at the entry to inlet box). This provides greater confidence that there is not a calculation error; although there is some flow disturbance around the static ring at the entrance to inlet box affecting results. For this reason the more conservative K value of 1 has been used in determining flow from fan static rings. The inlet box Loss factor K is determined by solving for the value of K that gives the same velocity v1 (from formula 14 at entrance to inlet box) to the Velocity v1 determined from the mass flow calculated by pitot traverse divided by the area and the density at the entrance to inlet box. The paragraphs above have demonstrated the method of calibrating the shock factor or loss coefficient in the flow calculations in main fan flow readout using differential area measurement techniques.
UNDERGROUND PRESSURE QUANTITY SURVEY

The Pressure Quantity Survey was also conducted with one barometer located on surface and surface WBT and DBT readings were taken every 30 minutes by control room operator. The results of PQ survey were used to calibrate the simulation model to results measured in survey. The original mine model resistance and calibrated resistance using PQ survey were 0.09087 Ns²/m⁸ and 0.0669 Ns²/m⁸ respectively. To get a reasonable agreement with the ventilations Survey, adjustments were made to model roadway dimensions to better reflect those measured in survey ~ 0.4 m increase in height was applied to most roadways, the critical overcast resistance was set to the measured value of 0.04663 Ns²/m⁸ and the K factor (Friction Factor) for smooth blasted type roadways was reduced from 0.012 to 0.007837kg/m³. The changes in these values in the model reduced the mine resistance from 0.06645 Ns²/m⁸ to 0.03991 Ns²/m⁸ and increased development face quantities by ~ 15 m³/s over the original model. The PQ survey and the pitot survey provided additional confidence on the validity of the simulation model and its application for the long term project scenarios.

The relative static pressures of each survey point were calculated assuming polytrophic flow using the presented in Chapter 6 of McPherson 2008 and compared with the methods by Hemp in Chapter 6 of Burrows 1989. In reality they are both the same method with a slightly different mathematical arrangement. Chapter 3 of McPherson 2008 gives details. However, evaluation did not result in same results that can be reasoned due to using real moist air densities calculated with ASHRAE LibHuAirPRop software rather than ideal gas densities used in equations.

**McPherson Formula**

\[ \begin{align*}
F_{12} &= \frac{u_2^2 - u_1^2}{2} + (Z_1 - Z_2) \cdot g - R \cdot (T_2 - T_1) \cdot \frac{\ln(P_2/P_1)}{\ln(T_2/T_1)} \\
p_{12} &= \rho_a \cdot F_{12}
\end{align*} \]

- \( p_{12} \) = Frictional Pressure Drop between stations 1 and 2 (Pa)
- \( \rho_a \) = Average density between stations 1 and 2 (kg/m³)
- \( F \) = Work done against friction between stations 1 and 2 (J/kg)
- \( u \) = average velocity at section (m/s)
- \( Z \) = height of station above Datum or Reduced Level (m)
- \( g \) = local acceleration due to gravity (m/s²)
- \( R \) = Mean gas constant for moist air (J/kg.K)
- \( T \) = Absolute Temperature at station (K)
- \( P \) = Barometric pressure at Station (Pa)

**Hemps Formula**

\[ \begin{align*}
p_{12} &= -(P_2 - P_1) - g \cdot \rho_a \cdot (Z_1 - Z_1) \\
F_{12} &= - \int v dP - g(Z_1 - Z_1) - g \cdot \int W dZ
\end{align*} \]

- \( v \) = Specific volume (m³/kg) i.e. \( 1/\rho \)
- \( W \) = Humidity Ratio (kg/kg) (kg water / kg air) in moist air

A summary of these equations is given in paper by a Prosser and Loomis, 2004. Apart from the humidity ratio term and the lack of velocity term in Hemps formula it is mathematically the same as McPherson's Formula for \( F_{12} \) (refer Chapter 3 McPherson, 2008 for details). During this underground PQ survey and measured velocity values, when the velocity term was removed from McPherson’s equation the relative static pressure results fall within 0.2 Pa with Hemps pressure equation. Therefore, this suggests that the use of either of the equations is of less significance unless there is large variations in measured velocities between two ventilation stations.
CONCLUSIONS

The main fan tests and underground PQ survey provided following assurances to the project:

- The main axial fan was tested through a range of operating points beyond currently perceived pressure stall point of 2.1 kPa. The fan test study has validated the fan curves with different pitch setting for use in ventilation simulation studies, which is to give a good operating safety margin from the maximum operating point of 2.6 kPa.

- The study has shown that, when in doubt w.r.t, the main fan curve stall zone, the fan tests provide assurance on the safety margin for the mine fans to operate. Nearly 500 Pa difference in the perceived fan stall point and maximum operating point during field observations for the identified fan pitch was noted.

- The underground PQ survey provides the valuable information in terms of accuracy of mine resistance values and K factors used in the simulation model. The model friction factor and resistance values used were conservative. When remodelled the using new friction factor derived from the underground PQ survey, the face quantities were increased by up to 15 m$^3$/s reflecting the operating mine conditions.

- The study has noted that for expansion project decision making, carrying out a desktop based simulation models provide lesser assurance for critical shaft and fan infrastructures decision making.

- Based on the field test in seeking the fan stall zone, it is noted that in this specific case, the stall zone suggested by the supplier was conservative and the main axial fan was at least 500 Pa away from the potential stall point in a simulation model. However, it is not the intention to operate at the maximum pressure. This finding has enabled the operation invaluable additional information in managing the risk and appropriate decision making.

- The paper also demonstrated the method of calibrating the shock factor or loss coefficient in the air flow calculations in main fan flow readout using differential area measurement techniques.

- The underground PQ survey data evaluated using two different methods has shown that the use of either of the equations is of less significance unless there is a large variation in measured velocities between two ventilation stations.

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