The challenge of measuring airflow through

MINE REGULATORS TO ALLOW REAL TIME VENTILATION MONITORING

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Abstract

The mathematical modeling of airflow through operating mine regulators is discussed. Results are used in the development of a computerised monitoring and simulation system to provide immediate or real time data on air behavior within each branch within an underground mine ventilation network through linking of sensors to the ventilation network simulation software.

Software has been developed to link real time information generated by mine ventilation monitoring sensors into the network program to undertake network simulations and allow interpretation of key system data and operational changes.

The outcome of the project is an online system which can report changes in the mine ventilation system, allow causes of changes to be isolated and rectified, improve balancing of available air throughout the mine and dispense with much of the labor used for underground ventilation measurement.

The main work activities involved in the research program have involved examination and modeling of regulators, software modification and considerable mine site testing and optimising activities.

1 Introduction

There is a move worldwide to remote or telemetric monitoring of mine atmosphere conditions. Robust, suitable and as required, intrinsically safe instruments are available for measurement of, for instance, gas concentrations, and air velocity and air pressure. These are often tied to extensive mine monitoring and communication systems.

One approach to establishing air quantity through a ventilation branch is through measurement of differential pressure across an opening or regulator. Mathematical relationships are available to relate (with some qualification) pressure drop and quantity through a regulator orifice placed symmetrically in a round flow conduit. However these can, at best, only be used to approximate mine regulator behavior due to:

- the irregularity of mine regulators in shape and symmetry and their positioning in normally roughly square or rectangular mine airways
- the construction of the mine regulator opening which may result from, for instance, the operation of louvers, a sliding door, window or curtain or placement of drop boards
- Uncontrolled air leakage through the regulator or adjacent bulkhead.

The study describes efforts to characterise or mathematically model regulators. It then describes how this information is used in the development of a computerised monitoring and simulation system to provide immediate or real time information on each branch within an underground mine ventilation network through linking of sensors to the ventilation network simulation software.

Software has been developed to link real time information generated by mine ventilation monitoring sensors into the network program to undertake network simulations and allow interpretation of key system data and operational changes.

The outcome of the project is an online system which can report changes in the mine ventilation system, allow causes of changes to be isolated and rectified and improve balancing of available air throughout the mine.

It is envisaged that in time the real time model will be an integral part of a real time mine wide planning, monitoring and control software platform and will be updated in real time along with the mine plan. The main steps involved in examination and modelling of regulators, software modification and considerable mine site testing and optimising activities are described.

2 Theory of regulators

A regulator is an artificial resistance (in the form of shock loss) introduced into an airway to control airflow.

2.1 Types of regulators

Regulators placed in mine air circuits may vary from well-engineered devices with a long life to temporary roughly constructed arrangements that achieve a practical purpose or 'the job in hand.'

Some of the more permanent devices take the following forms.

Drop board regulators

Drop board regulators are a popular form of variable resistance regulators. They can consist of two vertical steel rails placed on each side of the airway (usually against bulkhead pillars) into which large wooden boards are slotted from the ground up. Installation and alteration can be very labour intensive. More boards in place result in a smaller air opening and consequent generation of a higher shock loss. Personnel access through them is usually difficult.

Louvers

Louvers form a variable resistance regulator. Similar to domestic window louvers, they are usually made of steel. The shock loss is related to the degree to which the louvers are open.

Rubber flaps

Rubber flaps can be used where vehicle access is required through a regulator and a good seal is not required. The flaps are hung from the back or roof, usually from a beam, such that they overlap. Vehicles can pass through them without the driver stopping the vehicle or opening the flaps.

Canvas stoppings

These regulators consist of canvas stiffened by steel bars. The canvas is tied to the back and allowed to hang freely across the drift. Air pressure should ensure that the canvas forms a reasonable seal against adjacent bulkhead pillars. The height of the canvas is adjusted to vary the required shock loss.

Ventilation doors

Ventilation doors allow passage of personnel, vehicles and materials. They can completely seal off an airway (solid doors) or partially seal by incorporating an opening often covered by a sliding panel.

Ventilation bulkheads

In cases where a small amount of air is required a hole may be placed in a bulkhead. A sliding door may be used to control flow through the opening.

2.2 Derivation of regulator equation

A regulator can be described as a large thin plate installed in a fluid conduit with an orifice. When a difference in pressure exists between the two sides fluid flows in the pattern shown in Figure 1.

On the low pressure side the fluid issues as a converging jet in line with the centre of the orifice. The jet converges to its smallest area at a distance of about half the orifice diameter (Le Roux, 1979).

This area is called the 'vena contracta' (A_c at Fig. 1). The ratio between vena contracta and orifice area is the 'coefficient of contraction', C_c (A_c/A_r at Fig. 1).

McElroy (1935) found that the C_c value is a relation between the ratio of the orifice and airway cross sectional area, N (A_r/A at Fig. 1), and Z, which is an empirical factor designated as the contraction factor, which is expressed as:

$$C_c = \sqrt{\frac{1}{Z - ZN^2 + N^2}} \tag{1}$$

Values of Z vary according to the edge shape of the orifice. Since most regulators are square edged, a Z value of 2.5 is most commonly used in calculating C_c. Bernoulli's equation can be applied to both sides of the orifice as shown in Figure 1 in order to calculate the velocity and hence the airflow quantity.

A correction must be made for the contraction of the jet at the vena contracta. Since the orifice is larger than the vena contracta, orifice velocity is lower than in the vena contracta. The velocity equated based on Bernoulli's equations is the velocity at the vena contracta. Therefore, the velocity at the orifice can be obtained with the following equation:

$$V_2 = C_c\sqrt{\frac{2\Delta P_s}{\rho}}\,\frac{1}{\sqrt{1-N^2}} \tag{2}$$

where C_c is the coefficient of contraction, as described before. Since airflow quantity through regulator $Q = V_2 A_r$, it follows that:

$$Q = C_c\sqrt{\frac{2\Delta P_s}{\rho}}\,\frac{1}{\sqrt{1-N^2}}\,A_r \tag{3}$$

where A_r is orifice opening area in m^2.

3 Field tests of regulators

Field tests were conducted at the University of Queensland Experimental Mine (UQEM) to verify air behavior in flow through regulators. Parameters measured were airflow quantity and pressure drop across the regulator.

From pressure drop measurements, airflow quantity through the regulators can be calculated with Equation 3. Results of this calculation can be compared with measured values and the reasons for significant differences investigated.

3.1 UQEM tests

The UQEM regulator is the drop board type as shown in Figure 2. Results of this test are summarised in Table 1.

Based on DP_s measured, predicted airflow quantity through the regulator, Q, was then calculated with Equation 3. Values of Q were compared with the measured quantity, $Q_{m,}$ as set down in Table 1 and Figure 3. It can be seen from both the table and figure that the measured quantity is consistently larger than predicted. There are several possible reasons as follows.

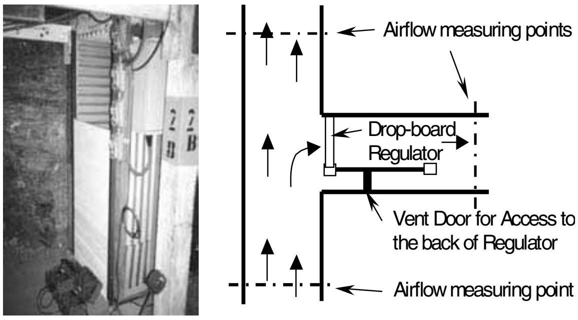


Figure 2 Drop board regulator tested at UQEM

Error during measurement

It is common for operator-induced errors to occur during mine drift measurement especially in small cross sectional airways. The authors experienced difficulty when measuring air velocity by continuous traversing because of limited space to move freely. Also, an author's body provided a significant obstacle to the airflow.

Non-symmetrical condition and shape

Equation 3 was derived based on a circular orifice in the middle of a regulator plate. The UQEM regulator opening is located on the upper side and opening is rectangular leading to distorted air patterns.

Leakage

Leakage occurs due to the presence of gaps between boards and between the regulator frame and the airway walls. The leakage quantity depends on

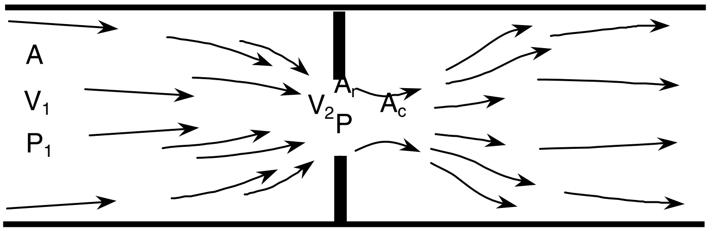


Figure 1 Airflow pattern through an orifice (after Burrows et al, 1989)

regulator construction and the differential pressure drop across the opening.

An approach is proposed to model the difference as air leakage since measurement error and the non-symmetrical condition were difficult to quantify. Therefore, the airflow quantity through the regulator can be expressed as:

$$Q = C_c \sqrt{\frac{2\Delta P_s}{\rho}} \frac{1}{\sqrt{1-N^2}} A_r + Q_l \qquad (4)$$

where Q_l is the leakage quantity. Thus Q_l needs to be quantified. An approach to this modelling is developed.

3.2 Relationship between airflow quantity and regulator resistance

The regulator can be treated as a set of two parallel airways namely:

- the regulator opening
- the leakage paths, that is passages through and around the regulator other than the regulator orifice itself.

This can be illustrated as in Figure 4.

Therefore, the total resistance of regulator (R_t) can be modeled to consist of the regulator opening resistance (R_o) and the leakage path resistance (R_l). When the regulator is in a fully closed condition, the air flows through the leakage path only. Airflow quantity through the regulator opening is calculated using the basic square law ($DP_s=RQ^2$). Based on this equation and Equation 3, the relationship between R_o and A_r can be established as follows (Gillies et al, 2002).

Figure 3. Comparison between measured and predicted quantity

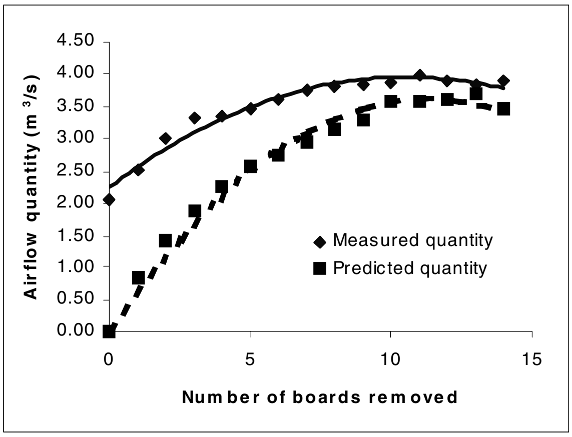
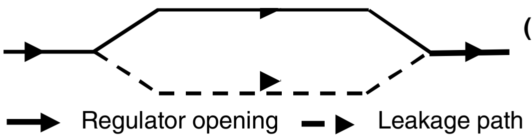


Table 1 Summarised results of UQEM test.

Condition	ΔP_s Pa	Q_m m³/s	Q m³/s	Difference %
Fully closed	163	2.05	0.00	n/a
1 board off	125	2.53	0.82	209.8
2 boards off	96	3.02	1.44	109.6
3 boards off	73	3.33	1.89	76.0
4 boards off	58	3.35	2.27	47.7
5 boards off	47	3.46	2.58	34.3
6 boards off	36	3.62	2.74	32.0
8 boards off	25	3.82	3.14	21.5
10 boards off	19	3.86	3.58	7.8
12 boards off	12	3.90	3.61	8.1
14 boards off	7	3.89	3.46	12.4

Figure 4 Airflow paths in regulator.



$$R_o = \frac{\rho}{2C_c^2}\left(\frac{1}{A_r^2} - \frac{1}{A^2}\right) \qquad (5)$$

where A is the airway cross sectional area. Since this equation does not take leakage into account, the actual regulator resistance will be different to the one calculated by Equation 5.

Thus actual resistance is R_t. R_t is made up of R_o and R_l in parallel configuration and so the relationship between them can be established. Since R_o has been quantified by Equation 5, R_l has to be quantified also to allow R_t to be calculated. Thus based on the measured pressure drop, the airflow quantity through the regulator can be determined.

To do this, R_o is first calculated using Equation 5, and then the total resistance is calculated using the square law based on the measured pressure drop and the measured airflow quantity. R_l then can be calculated using the parallel airways resistance relationship. Table 2 shows the calculated resistance of the regulator tested at the UQEM.

To quantify R_l a plot against regulator opening area was made, as shown in Figure 5. It was found that

$$R_l = 32.734e^{1.1631Ar}$$

Therefore, the total regulator resistance, R_t could be calculated using the parallel airways resistance relationship.

The airflow quantity was then re-calculated using the square law based on the new R_t. Results of this was then compared with measured values, Q_m, as summarized in Table 3 and Figure 6. It can be seen from both table and graph that the difference is at all times less than 10 percent which is well within practical underground measurement tolerance and therefore this new equation is sufficiently reliable to be employed for further analysis.

The relationship between the regulator opening area and total resistance can be derived as shown in Figure 7. Based on this, pressure and airflow quantity relationships can be calculated from mine regulator impedance characteristic curves. These can be drawn for different mine configurations as shown in Figure 8. The three curves shown illustrate relationships for one, three and five boards off from the regulator.

4 UQEM real time mine ventilation system

The aim of this mine ventilation research was to develop a computerised monitoring system to provide immediate or real time simulated information on each branch within an underground ventilation network. The system measures airflow or air pressure changes in selected ventilation branches and simulate flows through all other branches. This new approach to ventilation provides improved understanding of airflows through all mine sections.

The popular ventilation simulation modeling program Ventsim has been used as a simulation engine within the system. This software has been altered to accept real time information generated by underground mine ventilation monitoring sensors, undertake network simulations and interpret key system data and operational changes. Once the simulation program has updated readings it can remodel the whole mine system, report the flows in all branches and compare individual branch readings with expected values.

The UQEM was used to test the integration of a telemetry system into the Ventsim network analysis environment. An isometric plan of the UQEM is shown in Figure 9. The mine airflow monitoring system included consisted of one El-Equip ‘Flosonic’ and two vortex shedding Sieger BA5 air velocity sensors.

The FloSonic air velocity sensor is an ultrasonic anemometer measuring the average air velocity value across a drift with very good accuracy (Casten et al, 1995 & McDaniel et al, 1999). The initial aim of this testing was to use the system to monitor changing ventilation conditions, to establish airflow characteristics within the UQEM and to observe the resimulated network results.

Achievement of the main research aim was facilitated with the development of a real time solution requiring data communication links between the various system components. These components included the UQEM telemetry monitoring system, the telemetry control software, the developed data manipulation applications, a File Transfer Protocol (FTP) application and a modified real time version of Ventsim. Details of the integration of the UQEM real time ventilation monitoring system including Ventsim modification have been described by Gillies et al (2000).

5 Trials of the UQEM system

The performance of the modified airflow real time ventilation monitoring system at UQEM was evaluated. Parameters examined in this trial were:

- the ability of the system to detect changes in the mine ventilation system
- the accuracy of airflow quantity prediction in unmonitored branches within the mine ventilation network based on the number of sensors linked to the system
- constraints limiting performance of the system.

5.1 Test results

Four trial scenarios were implemented in the evaluation tests:

I. The inclined shaft door was open, and the regulator in 116’ level set on fully open.

II. The inclined shaft door was open, and the regulator was set 1/5 open with 12 boards on.

III. The inclined shaft door was open, and the regulator set on fully closed.

IV. The inclined shaft door was closed, and the regulator was set on fully open.

For the purpose of the tests the main shaft and the double doors on the 140’ level were closed and the door on the 154’ level was removed to increase airflow through the 116’ adit and inclined shaft.

During the tests field measurements using a calibrated vane anemometer and pressure transducer were conducted at the 116’ adit, 116’ regulator, inclined shaft and ventilation drive on the 140’ level past the Dead Man’s Pass as shown in Figure 10 and referenced as Station 26-11.

Results of these measurements were then compared with predicted values generated from the real time Ventsim models. The aim here was to evaluate the accuracy of airflow quantity prediction in unmonitored branches.

The real time Ventsim models were run with one to

Table 2 UQEM regulator resistances

Condition	R_t Ns^2/m^8	R_o Ns^2/m^8	R_l Ns^2/m^8	A_r m^2
Fully closed	38.65	∞	38.65	0
1 board off	19.46	186.77	42.43	0.09
2 boards off	10.56	46.39	38.61	0.18
3 boards off	6.58	20.39	35.31	0.27
4 boards off	5.17	11.29	49.52	0.36
5 boards off	3.93	7.08	60.21	0.45
6 boards off	2.75	4.80	46.76	0.54
8 boards off	1.71	2.53	54.71	0.72
10 boards off	1.28	1.48	246.09	0.90
12 boards off	0.79	0.92	140.23	1.07
14 boards off	0.46	0.59	37.87	1.25

Table 3 Comparison between measured and new predicted quantity

Condition	Q_m m^3/s	New R_t Ns^2/m^8	New Q m^3/s	Difference %
Fully closed	2.05	32.73	2.23	-8.0
1 board off	2.53	17.49	2.67	-5.2
2 boards off	3.02	10.80	2.98	1.1
3 boards off	3.33	7.27	3.17	5.1
4 boards off	3.35	5.18	3.35	0.0
5 boards off	3.46	3.84	3.50	-1.1
6 boards off	3.62	2.93	3.51	3.1
8 boards off	3.82	1.81	3.72	2.7
10 boards off	3.86	1.17	4.03	-4.3
12 boards off	3.90	0.78	3.93	-0.8
14 boards off	3.89	0.52	3.68	5.7

Figure 5 Quantification of resistance for leakage paths

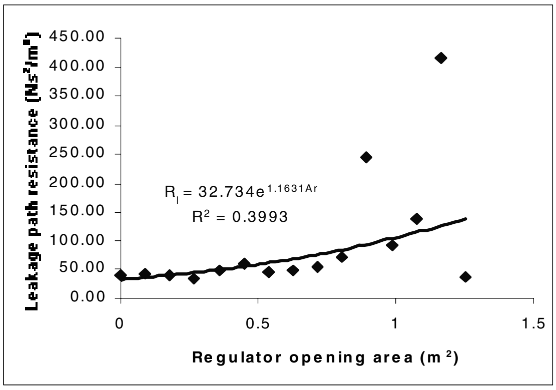
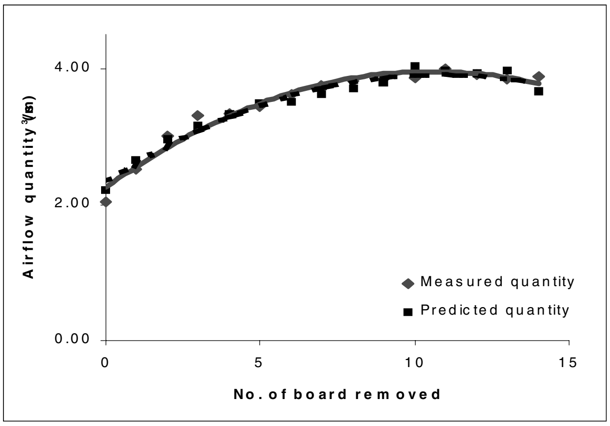


Figure 6 Comparison between measured and new predicted quantity



three real time airflow sensors link to the software and reporting to the Ventsim program as 'fixed quantity' branch quantity values. Theoretically more sensors linked to the system should give greater accuracy as real measurements from a greater mine geographic area and representing more realistic conditions of the mine are available.

Due to the electrical sensing problems encountered with the BA5 vortex-shedding sensor installed in 116 Adit, it was decided that the outputs from that sensor would not be included in the tests. A summary of the results is shown in Table 4.

It can be seen that the UQEM real time Ventsim monitoring system performs with reasonable accuracy, although some differences in quantities were larger than 10 percent as shown in the table. For example, the quantities through inclined shaft when the door connected to inclined shaft in 140' level was closed. However, this is acceptable, since the quantities predicted (ranging around 0.8-0.9m³/s) and measured (around 0.6m³/s) in these cases were low.

Results in Table 4 indicate that the system can predict changes within the mine ventilation system. The system predicted decrease in the regulator quantity as the regulator opening decreased. It also predicted decrease in quantity through the inclined shaft as the door was closed.

Within these tests no significant difference between the accuracy of one and two sensors linked to the system was observed. However, it cannot be concluded that this would be the case in a large operating mine since the location of the sensors will also have an important influence.

5.2 Constraints of the system

As described before, one aim of these tests was to identify constraints that might limit performance of the system. One major point of interest is the delay time or transient period between the instant of a change and when the system detects the change. The results of some changes are summarised in Table 5.

Figure 7 Relationship between new total resistance and regulator opening area

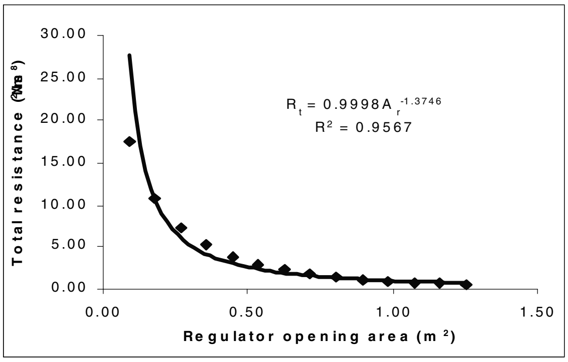


Figure 8 UQEM regulator characteristic curves

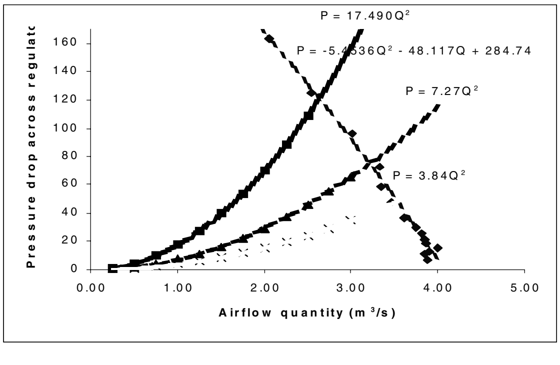


Table 5 Summary of the transition time observed

Changes	Time
Regulator fully open to 12 boards	70 seconds
Regulator 12 boards to fully closed	36 seconds
Regulator fully closed to fully open	84 seconds
Inclined shaft door open to closed	72 seconds
Inclined shaft door closed to open	75 seconds

The transient period in UQEM is short and therefore is not of great significance in interpreting the network system. However, in large-scale mines, the period can be up to 10 minutes. What this means is that reliance cannot be placed completely on 'real time' airflow readings being instantaneously correct as reported for all branches within a mine ventilation simulated network.

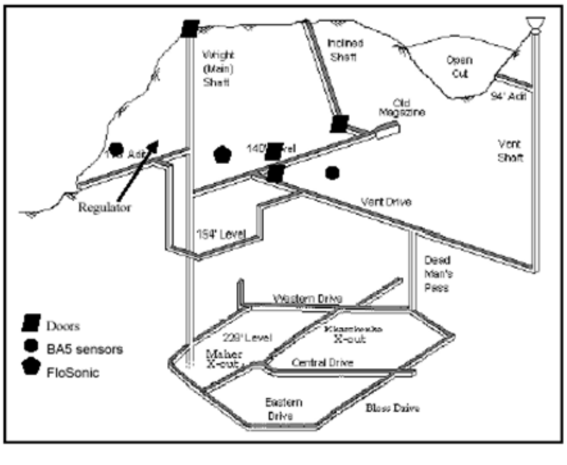
There is nothing that can be done to eliminate this characteristic as it is representative of the nature of airflow within underground mines. A change which leads to a hazardous condition may go unreported for time interval of this transient period. Of course changes in mine ventilation systems measured manually are rarely immediately picked up but the limitations of an automatically reporting real time system should be recognised.

6 Conclusions

Efforts to characterise or mathematically model a number of operating mine regulators have been described. Underground measurements have indicated that theoretical calculations to predict airflow quantity through practical mine regulators based on measured pressure drop are inadequate. The theoretical approaches are limited as they are based on prediction of fluid flow through a circular orifice in the middle of a plate whereas most mine regulators have a rectangular non-symmetrically positioned orifice. Also, most importantly, there is air leakage through the regulator bulkhead frame and gaps that increase actual quantity compared to that predicted.

The way to overcome this difference is to quantify the resistance of the leakage path based on regulator opening area and then recalculates the total resistance of the regulators. The relationship between leakage path resistance and regulator opening area varies, but the resistance should increase along with an increase in opening area. Based on measured pressure difference, the airflow quantity can be predicted accurately using the basic square law. It requires field

Figure 9 Plan of UQEM showing location of doors and sensors



measurement to quantify the leakage path resistance of each regulator, since each regulator has its own leakage characteristic (size and number of gaps, etc). This is a tedious work, since the regulators can be set with many opening areas. However, it was found that with limited measurement data, prediction results are still accurate within acceptable tolerance appropriate to understanding mine airflows.

The aim of the study was to gain greater understanding of a computerized monitoring system to provide immediate or real time simulated information in each branch of an underground ventilation network.

The system measures airflow in selected ventilation branches and simulates flows through all other branches. An investigation was undertaken as to whether the UQEM Real Time Airflow Monitoring system can detect changes within the mine ventilation system, examine accuracy of the system and identify constraints that will limit performance of the system.

As a result of trials, it was demonstrated that the system was able to detect changes occurring within the mine ventilation system and was also able to predict the changes accurately. Limitations caused by transient period delays have been examined.

Updating of simulation models from use of real time data has also been discussed. It is envisaged in the future that the ventilation model would be an integral part of a real time mine wide planning, monitoring and control software platform from which the model would be updated in real time.

Acknowledgement

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Table 4 Summary of trial results at UQEM

Scenario	Quantity (m^3/s)					
	Predicted	Measured	*Diff (%)*	Predicted	Measured	*Diff (%)*
One sensor linkage						
	Regulator			116' adit		
I	3.1	2.8	*-9.7*	3.9	4.1	*5.0*
II	2.2	2.1	*-2.9*	3.8	3.8	*-0.4*
III	1.7	1.3	*-22.0*	3.7	3.7	*0.2*
IV	3	2.8	*-6.7*	4.9	5.3	*8.4*
	Inclined shaft			Station 26-11		
I	2.8	2.8	*-0.4*	9.1	9.1	*-0.1*
II	2.7	2.8	*4.3*	8.9	9.0	*1.2*
III	2.7	2.8	*2.7*	8.8	8.7	*-0.9*
IV	0.9	0.6	*-38.7*	8.8	9.0	*1.9*
Two sensors linkage						
	Regulator			116' adit		
I	3.1	2.8	*-9.7*	3.9	4.1	*5.0*
II	2.2	2.1	*-2.9*	3.8	3.8	*-0.4*
III	1.7	1.3	*-22.0*	3.7	3.7	*0.2*
IV	2.8	2.8	*0.0*	4.9	5.3	*8.4*
	Inclined shaft			Station 26-11		
I	2.8	2.8	*-0.4*	9.1	9.1	*-0.1*
II	2.7	2.8	*4.3*	8.9	9.0	*1.2*
III	2.7	2.8	*2.7*	8.8	8.7	*-0.9*
IV	0.8	0.6	*-31.0*	8.8	9.0	*1.9*

Figure 10 Schematic diagram of UQEM ventilation system