THE MEASUREMENT OF AIRFLOW THROUGH REGULATORS

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ABSTRACT

There is a trend world wide to remote or telemetric monitoring of mine atmosphere conditions. Robust, proper and intrinsically safe as required instruments are available for measurement of, for example, gas concentrations, air velocity and air pressure. These are often tied to wide-ranging mine monitoring and communication systems.

One very reliable 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 qualifications) pressure drop and quantity through an orifice placed symmetrically in a round flow conduit. However these can only be used to approximate mine regulator behaviour due to variability in construction, questions of symmetry and leakage

Efforts to characterize and/or mathematically model a number of types of operating mine regulators are described. Results can be used in the development of a computerized monitoring and simulation system to provide immediate or real time data on air behaviour within each branch within an underground mine ventilation network through linking of sensors to the ventilation network simulation software. This new approach to ventilation provides improved understanding of airflows through all mine sections.

INTRODUCTION

There is a move world wide 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, 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 (Gillies et al, 2002). Mathematical relationships are available to relate 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 behaviour due to:

- The irregularity of mine regulators in shape and symmetry and their positioning in normally roughly square or rectangular mine airways,

- Whether air has to change direction before passing through the regulator,
- The construction of the mine regulator opening which may result from, for instance, the operation of louvres, a sliding door, window or curtain or placement of drop boards, and
- Uncontrolled air leakage through the regulator or adjacent bulkhead.

The study describes efforts to characterize or mathematically model a number of operating mine regulators. The information is then used in a computerized 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. 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. Ventilation network analysis 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 (Gillies et al, 2002).

This paper describes only some of the steps involved in the research project with particular emphasis on the examination, characterisation and modelling of various types of mine ventilation regulators used the both coal and metalliferous mines.

THEORY OF REGULATORS

A regulator is an artificial resistance (in the form of shock loss) introduced into an airway to control airflow. When airways are arranged in parallel and a prescribed quantity of air is made to flow through each branch, then "controlled splitting" is utilised. The branch with the highest resistance initially is termed the "free split". The free split may remain untouched or "free" of added impedance during the controlled splitting exercise. Other branches can have resistance added to them by the use of regulators that induce a shock loss of the required amount to deliver assigned airflow along all branches.

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 or steel 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 or vehicular access through them is usually difficult.

Louvres

Louvres form a variable resistance regulator. They are usually made of steel and are similar to domestic window louvres. The shock loss is related to the angle at which the louvres 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.

Fabric or flexible material

These regulators may consist of fabric of flexible material stiffened by steel bars. The material may be tied to the back and allowed to hang freely across the drift. In this case air pressure should ensure that the material forms a reasonable seal against adjacent bulkhead pillars. The height of the material can be adjusted to vary the required shock loss. Alternatively the stiffened material may form a "roller door" arrangement that can be fully opened for passage of vehicles or blast concussion. The roller door opening action may be motorised, sometimes through remote control, to allow easy setting to achieve a range of shock losses

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.

Derivation of Regulator Equation

A regulator can be described as a large thin plate installed in a fluid conduit with an orifice cut in it. When a difference in pressure exists between the two sides the plate, fluid flows through the orifice in the pattern shown in Figure 1. The fluid enters the orifice from all directions on the high pressure side on the low pressure side it 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, 1990). 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, Fig. 1).

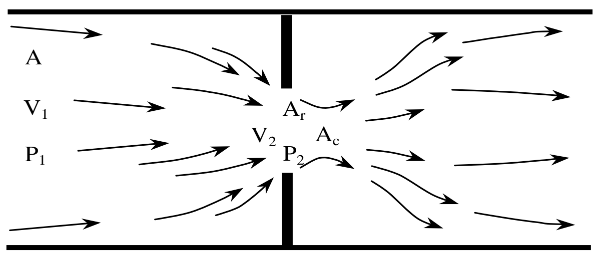

Figure 1 Airflow pattern through an orifice (after Burrows et al, 1989).

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:

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

Values of Z vary according to the edge shape of the orifice. Table 1 shows the Z factor for some constructions.

Table 1 Contraction factors (Hartman et al, 1997).

Edge	**Z**
Formed	1.05
Rounded	1.50
Smooth	2.00
Square	2.50
Sharp	3.80

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 of the air 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:

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

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

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

where A_r is orifice opening area in m^2.

FIELD TESTS OF REGULATORS

Field tests on several types of regulators were conducted at various underground metalliferous and coal mines. Initially verification of air behaviour in flow through regulators was investigated. Parameters measured were airflow quantity and pressure drop across regulator. From pressure drop measurements, airflow quantity through regulators can be calculated with Equation 1. Results of this calculation can be compared with measured values and the reasons for significant differences investigated.

Drop board regulator tests

The regulator tested initially was a typical drop board regulator, as shown in Figure 2. Results of these tests are summarized in Table 2.

Based on ΔP_s measured, predicted airflow quantity through the regulator, Q, was then calculated with Equation 1. Values of Q were compared with the measured quantity, Q_m, as set down in Table 2 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.

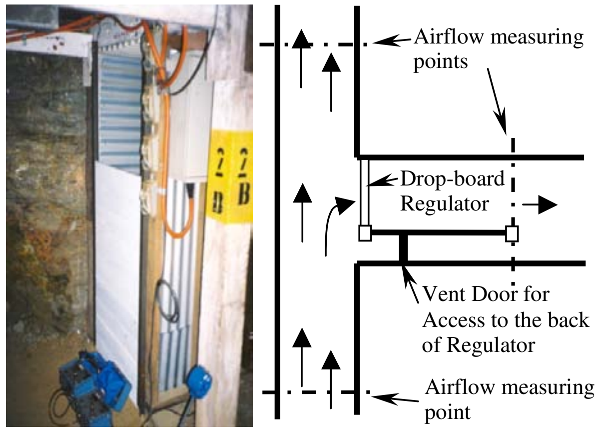

Figure 2 Drop board regulator tested.

Table 2 Results of drop board regulator test.

Condition	ΔP_s Pa	Q_m m^3/s	Q m^3/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
7 boards off	30	3.75	2.96	26.6
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

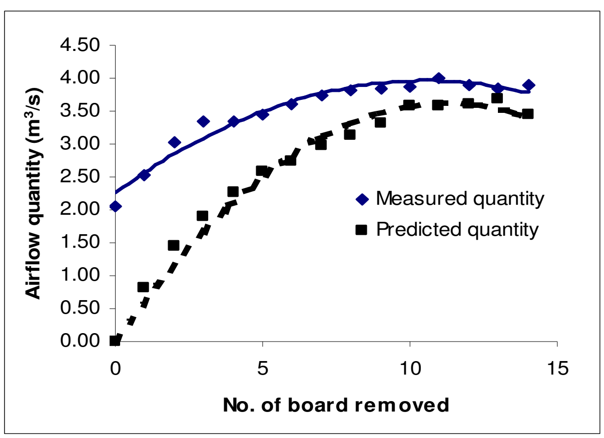

Figure 3 Comparison between measured and predicted quantity of air passing through regulator

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 vane anemometer traversing because of limited space to move freely. Also the body of the underground person provides a significant obstacle to airflow.

Non-symmetrical condition and shape

Equation 1 was derived based on a circular orifice in the middle of a regulator plate. The regulator opening under study is rectangular, has square edges and is located on the upper side and opening is rectangular not round leading to distorted air patterns. In addition the air turns through a sharp right angle before entering the regulator

Leakage

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

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

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

Relationship Between Airflow Quantity and Regulator Resistance

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

1. The regulator opening and
2. 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.

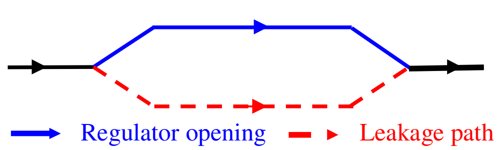

Figure 4 Airflow paths in regulator

Therefore, the total resistance of regulator (R_t) can be modelled 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 ($\Delta P_s = RQ^2$). Based on this equation and Equation 1, the relationship between R_o and A_r can be established as follows.

$$\sqrt{\frac{\Delta P_s}{R_o}} = C_c \sqrt{\frac{2\Delta P_s}{\rho}} \frac{1}{\sqrt{1-N^2}} A_r$$

$$\cancel{\sqrt{\Delta P_s}} \frac{1}{\sqrt{R_o}} = C_c \sqrt{2} \cancel{\sqrt{\Delta P_s}} \frac{1}{\sqrt{\rho}} \frac{1}{\sqrt{1-N^2}} A_r$$

$$\sqrt{R_o} = \frac{1}{C_c A_r} \sqrt{\frac{\rho(1-N^2)}{2}}$$

$$R_o = \frac{\rho(1-N^2)}{2C_c{}^2 A_r{}^2}, \text{ Since } N = \frac{A_r}{A}, \text{ thus}$$

$$R_o = \frac{\rho}{2C_c{}^2 A_r{}^2} \frac{\rho}{2C_c{}^2 A^2}$$

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

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 the equation above. 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 2, 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 2, 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 3 shows the calculated resistance of the regulator tested.

Table 3 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
7 boards off	2.13	3.42	48.32	0.63
8 boards off	1.71	2.53	54.71	0.72
9 boards off	1.42	1.92	72.25	0.81
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

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 can be calculated from:

$$\frac{1}{\sqrt{R_t}} = \frac{1}{\sqrt{R_o}} + \frac{1}{\sqrt{R_l}}$$

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

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

And so the total regulator resistance, R_t can be calculated. The airflow quantity was then re-calculated using the square law based on the new R_t. Results of this were then compared with measured values, Q_m, as summarized in Table 4 and Figure 6.

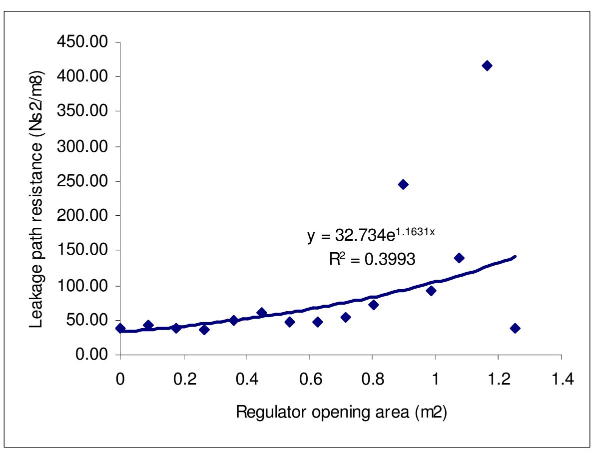

Figure 5 Quantification of resistance for leakage paths.

It can be seen from both the table and the 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.

Table 4 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
7 boards off	3.75	2.28	3.63	3.4
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

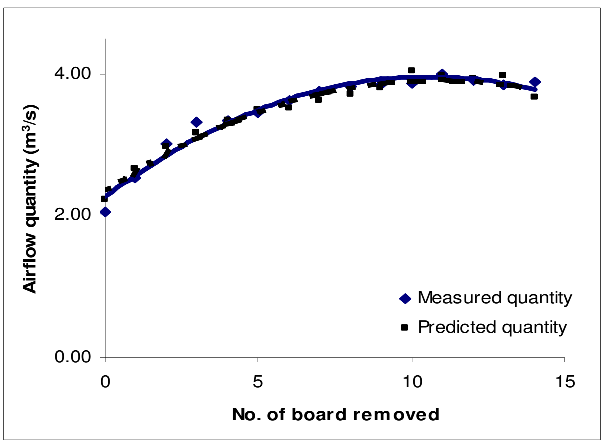

Figure 6 Comparison between measured and new predicted quantity.

From these 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 from Table 4 for one, three and five boards off the regulator.

An investigation was conducted to check whether the test method maintained accuracy with less measurement data. It was found that with half the number of measurements taken (removing two boards at one time instead of one board) differences remained mostly less than

10 percent and the method was still considered reliable.

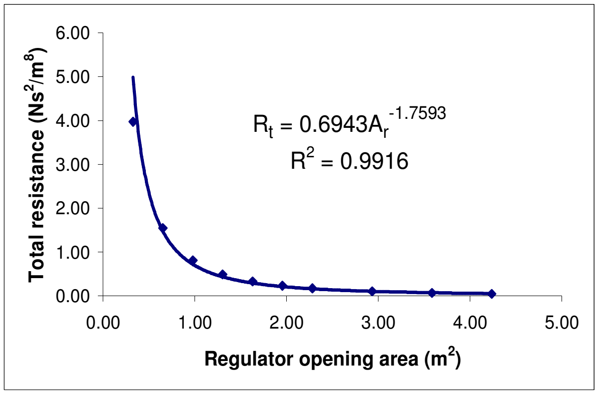

Figure 7 Relationship between new total resistance and regulator opening area.

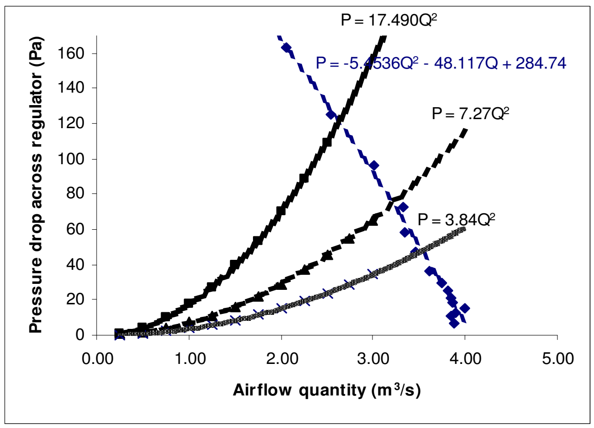

Figure 8 Drop board regulator characteristic curves.

C-section regulator tests

Similar tests were conducted on Drop Board style C-section regulators. Figure 9 shows a photographic view and the engineering drawing of a C-section regulator used by an Australian mine. The regulators were installed in either half or full sizes depending on the magnitude of the airflow regulation requirements and the locations.

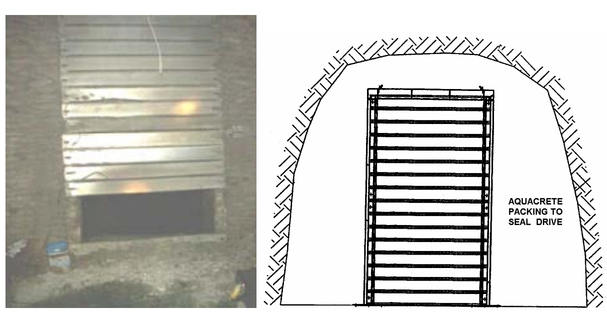

Figure 9 Photographic view and engineering drawing of a half size C-section regulator.

A half size ventilation regulator may consist of up to a total of 16 C-section galvanised steel boards which are secured with humpback split pins to the frame structure. The full sized version is two of these regulator frames placed side by side. The frame structure is secured in place using rock bolts to the concrete floor base. Packing is used to seal the drive around the regulator frame structure. Dimensions of each C-section board are 1.65 m in width and 0.2 m in height. The maximum opening area of a half size C-section regulator is 5.28 m^2.

Results of the initial test on one of the half size C-section regulators are shown in Table 5. Several test series were also undertaken to verify the relationship between the equivalent total regulator resistance, R_t, and equivalent opening areas, A_r at various locations at the same mine. Figure 10 shows the calculated relationships between R_t and A_r for the C-section regulators. It can be seen that the relationships are similar to the relationship established from the drop board regulator tests.

Table 5 Results for one of the C-section regulator tests.

Condition	**ΔP_s** Pa	**Q_m** m^3/s	**Q** m^3/s	**Difference** %	**R_t** Ns^2/m^8
Fully closed	385	6.3	0.0	n/a	9.70
1 board off	395	8.7	5.4	62.4	5.22
2 boards off	375	14.6	10.4	39.8	1.76
3 boards off	370	18.9	15.6	21.4	1.04
4 boards off	348	27.4	20.1	36.0	0.46
5 boards off	345	33.5	25.1	33.5	0.31
6 boards off	325	41.3	29.3	41.1	0.19
7 boards off	325	45.1	34.2	31.9	0.16
9 boards off	290	52.4	41.7	25.8	0.11
11 boards off	245	62.3	47.0	32.6	0.06
13 boards off	235	68.7	54.6	25.7	0.05

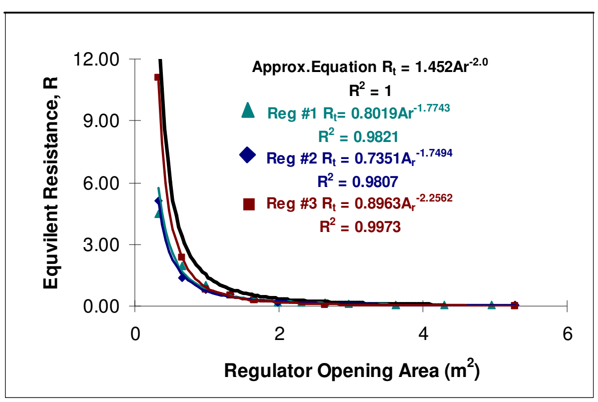

Figure 10 Relationship between R_t and A_r for C-section regulators.

In Figure 10, a theoretical relationship between the equivalent resistance and the opening area of a regulator similar to the approximation equation proposed by Le Roux (1990) was also included. The equation for calculating the size of regulator opening given the airflow quantity and pressure destroyed by the regulator is as follows.

$$A_r = C \times Q \sqrt{\frac{\rho}{\Delta P_S}}$$

where *C* is a constant.

This equation is based on equation 1 with assumptions made to account for the general mining conditions, for example, $C_C \cong 0.64$ and $\sqrt{(1-N^2)} \cong 1$. Therefore a value of 1.1 was suggested to replace these terms. As $R_t = \Delta Ps/Q^2$ rearranging the above equation, gives

$$A_r = 1.1 \times \sqrt{\frac{Q^2 \rho}{\Delta P_S}}$$

$$A_r = 1.1 \times \sqrt{\frac{\rho}{R_t}}$$

Therefore, R_t can be calculated from the following equation at standard air density of 1.2 kg/m^3.

$$R_t = 1.452 A_r^{-2.0}$$

In Figure 10, it can be seen that the equivalent total resistance calculated from the tests was lower than the theoretical regulator resistance. As mentioned before, the equivalent total regulator resistance takes into account also resistances of the leakage paths which parallel air paths through the regulator opening. It is expected that the values of R_t will be lower than the regulator resistance itself.

Louvre regulator tests

Tests were carried out on louvre type regulators. This type of regulator is popular in Australian coal mines and an example is shown in Figure 11. Generally a double vehicle door design has louvres placed within panels of both doors. The louvre blades can be adjusted to various angles to control airflow. In this test both left and right doors could be set at nine positions. Tests were undertaken both by holding one side fixed and varying the other and by varying both sides. Table 6 gives a summary of one of these test results sets, with calculated resistance values and equivalent opening areas for the louvre settings. Relationships between resistance and the equivalent opening areas are shown in Figure 12.

Figure 11 An example of a louvre regulator.

Table 6 Example of the louvre regulator test results.

Regulator Position				P_s (Pa)	Q (m^3/s)	R (Ns^2/m^8)	A_r (m^2)
Left	Angle	Right	Angle				
1	89	9	2.8	76	119.0	0.0054	3.41
1	89	8	14.5	86	117.7	0.0062	3.31
1	89	6	31	115	112.9	0.0090	2.94
1	89	5	45.2	172	105.1	0.0156	2.42
1	89	4	55	200	102.0	0.0192	1.98
1	89	3	65	235	88.5	0.0300	1.48
1	89	2	76	298	70.2	0.0605	0.87
1	89	1	89	387	52.1	0.1426	0.12
2	76	2	76	225	94.6	0.0251	1.62
3	65	3	65	125	118.6	0.0089	2.84
4	55	4	55	83	124.7	0.0053	3.85
5	45.2	5	45.2	50	132.1	0.0029	4.73
6	31	6	31	32	132.5	0.0018	5.76
9	2.8	9	2.8	20	140.4	0.0010	6.71

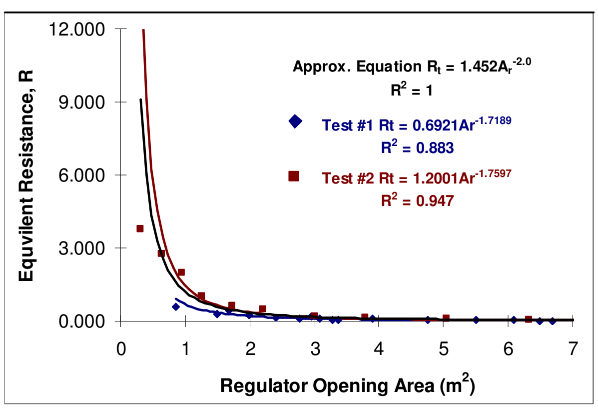

Figure 12 Relationship between resistance and equivalent opening area for louvre regulator.

It would appear that both aspects follow a similar relationship to that observed for the drop board or C-section regulators tested. There is no doubt that the resistance values increased as the equivalent opening areas decreased. However, it is suspected that due to the nature of fluid flow through louvre blade settings, the relationship between the resistance and equivalent opening areas would be a more complex than drop board flow behaviour. A literature review on louvre regulators indicated that only limited research had been conducted on louvre flow behaviour.

Roller door regulator tests

Use of a roller door as a ventilation regulator was examined. Adjustment of the height of this door is undertaken via an automated control system. There is very little information on the use of roller doors as ventilation regulators and on the automation of such a system. Basically at the start of every shift the ventilation supervisor would remotely turn on face or booster fans and adjust regulator positions as required via the integrated mine monitoring and control system. Airflow and/or differential pressure sensors could be incorporated as part of such an automated control system to monitor changes made.

For this study, a roller door was installed for trial purpose as shown in Figure 13. Basically the roller door works like a Venetian blind, that is the lifting belt (made from sling material) is attached at the bottom corners of the door leaf and runs up inside the side guides to the drive assembly at the top. As the drive winds the belt, it lifts the bottom beam and each successive horizontal aluminium beam stacks on the top causing the vinyl coated fabric to billow out on the both sides as the air is expelled.

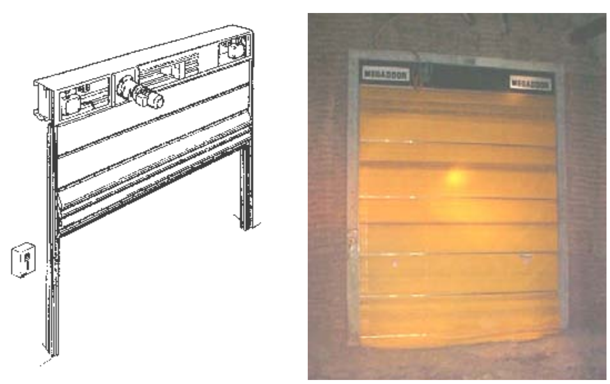

Figure 13 Schematic and photographic views of a roller door regulator

Several regulator characteristic tests were carried out to establish the relationship between R_t and A_r. The following figure shows the relationship between R_t and A_r for roller door tested. It should be noted that the air quantity and pressure was very low during the tests. Therefore, the calculation of equivalent resistance from measurements was difficult.

Also as one of the tests was conducted when the roller door was installed without a proper bulkhead built around it, a temporary brattice was erected to stop the airflows around the door. For this reason the leakage was substantial which means the equivalent resistance of the roller door regulator structure tested was much lower. As measurement was taken with the door fully closed it was possible to work out the equivalent resistance of the leakage paths around the door structure and then back calculate the resistance of the roller door only, R_{door}, without the leakage paths as shown in the Figure 14. It can be seen that it gives a much better comparison with the theoretical relationship between R_t and A_r.

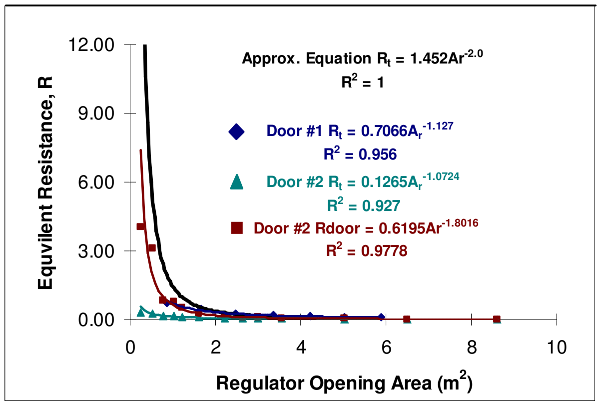

Figure 14 R_t vs. A_r for Roller Door regulator tested

It is proposed that further tests should be undertaken under higher air pressure and quantity conditions with proper bulkhead built around the roller door regulator.

CONCLUSIONS

Efforts to characterize 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 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.

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