A comparison of auxiliary ventilation systems and their predicted operational performances

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ABSTRACT

The objective of this paper is to examine some modern forms of auxiliary ventilation fabric ducting with streamline design fittings and the efficiency of construction practices. The most dynamic form of auxiliary ventilation is a moveable fan and ducting, which is easy to install and uses light weight fabric. The porous nature of some ducting construction results in leakage and loss of efficiency. Flexible fabric ducting is primarily associated with metalliferous mining and industrial material quarrying. Some applications are found in coal in stone/rock development and with use of dust scrubbers.

Forcing auxiliary ventilation systems employing circular fabric ducting have been examined. Leakage of air from ducting is affected by ducting material and construction methodology (such as welded or sewn), quality of installation, number of joints, total length, pressure differences between the inside and outside and diameter. The best ducting system with welded construction can have up to four times less leakage as compared with some systems with sewn construction. It is also evident that the sewn type ducting will deliver less air to working faces and require more fan power, hence higher operating costs to run when connected to the same fan.

A case study has also been undertaken to compare predicted operating costs of auxiliary ventilation systems connecting various types of ventilation duct fittings. The study also assesses the technical importance of streamline design with low aerodynamic resistance to reduce the shock losses of the duct fittings. It was found that the system connected with streamline designed fittings is able to provide some power cost savings and deliver more air compared with the system fitted with conventional fitting pieces.

Using a ventilation ducting system with a lower leakage and frictional characteristic represents a sound solution to new challenges faced by the industry for increasing demand for better quantities and quality of air delivered to working faces; this is due to higher production schedules and stricter mine health and safety regulations within the Australian mining industry.

INTRODUCTION

In underground mining operations intake and return airways are used to ensure the continual circulation of fresh air. Auxiliary ventilation system is needed for single entry or dead end workings such as development headings, drawpoints and some stopes. The most common form of auxiliary ventilation system is a system utilising fan and ventilation ducting that is relocatable as the mine develops. The most dynamic form of ducting is some form of fabric or canvas due to its lightweight design and ease of installation. However, the porous nature of these ducting materials results in leakage. Leakage of air from an auxiliary ventilation system is affected by ducting material and construction method (ie welded or sewn), quality of installation, number of joints, total length of ducting, diameter of the ducting, pressure differences between the inside and outside of the ducting, and quality (ie streamline design) and quantity of duct fittings. 'Streamline design of duct fittings' refers to various contour designed shapes of fittings that exist to ensure air is moving smoothly without significant turbulence in the auxiliary ventilation ducting systems.

Using a ventilation ducting system with a lower leakage and frictional characteristic will result in a direct saving on fan operating cost compared with a flexible ventilation ducting system with a standard or higher leakage and friction characteristic. Similarly, using a ventilation ducting system of lower leakage and frictional characteristic with the same kW rated fan will supply more airflow to the mine face as the system has less leakage. Other savings or advantages associated with the use of such a system include:

- potential capital saving on auxiliary fan as smaller fan can be used

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- potential saving both on capital and operating costs of ventilation fan
- potential savings on ventilation airways, raises, shafts and similar
- ease in providing a working place that complies with mine health and safety standards.

Using a ventilation ducting system with a lower leakage and frictional characteristic represents a sound solution to challenges faced by the industry for increasing demand of increased quality and quantity of air to be delivered to working faces due to higher production rates and stricter mine health and safety regulations within the Australian mining industry.

A brief review of prediction techniques for determination of losses due to leakage and friction has been undertaken. The main objective of this paper is to examine some modern forms of auxiliary ventilation fabric ducting and the efficiency of some streamline designed duct fittings. A case study has been undertaken to compare predicted operating costs of auxiliary ventilation systems connecting various types of ventilation duct fittings. The study also assesses the technical importance of streamline design with low aerodynamic resistance to reduce the shock losses of the duct fittings.

THEORY OF LEAKY DUCT

Early investigations of auxiliary ventilation ducting leakage performance assumed that the problem was purely practical and could be eliminated through proper installation and maintenance. Greater emphasis was placed on theoretical studies as it became apparent that some degree of leakage is inevitable even under the best conditions. These studies primarily focused on mathematical analysis of ducts with uniformly distributed leakage resulting in complex integrals that required numerical solutions. More recent work assumes the existence of discrete leakage paths and analyses the leaky duct as a ventilation network. Theory of leaky duct behaviour has been discussed in detail by the authors in previous papers as cited.

Magnitude of leakage

Many mining operations classify the quality of auxiliary ventilation ducting in terms of the percentage or volumetric leakage that occurs over a 100 m interval. This principle is scientifically unsound as variations in the air pressure along the length of the duct are not considered. A scientific method for expressing the magnitude of leakage from a ventilation column employs a leakage coefficient, a concept developed by the British National Coal Board (NCB). The leakage coefficient, L_C, is defined as the volume of air in m^3/s that leaks from a1000 m length duct subjected to a uniform pressure of 100 Pa.

Calculation of the leakage coefficient of a duct from first principles is a very complicated mathematical exercise as in practice ducts are never under uniform pressure. A British NCB leakage nomogram was developed to determine the leakage coefficient as referenced in metric units by Le Roux (1979). Robertson and Wharton (1980) developed a good approximation for the leakage coefficient as well.

In general, the pressure differential is always greatest adjacent to the fan between the inside and the outside of the ventilation duct connecting to the fan. Therefore a duct section near the fan will leak significantly more than a duct section further away. When the duct is extended the fan duty pressure will increase. As a result, leakage will increase from all sections of the duct. If two different sized columns are constructed and installed to equal standards it can be expected that the larger diameter duct will have a greater L_C on account of the increased area of the material seams and joints.

Other parameters commonly used to evaluate the performance of auxiliary ventilation columns are the volume and pressure increase ratios. The volume increase ratio is the volume handled by the fan divided by the actual volume delivered to the working face. The pressure increase ratio is defined as the pressure required to deliver a specified quantity through the duct under leaky conditions over the pressure required for delivering the same volume under leakless conditions. Roberts (1960) stated that the volume ratio and the pressure increase ratio are both approximately equal.

Mathematical solutions

Mathematical solutions have been proposed for duct leakages which take into consideration the pressure gradient along the duct. Using the assumption that leakage is uniformly distributed along the length of a duct Holdsworth, Prichard and Walton (1951) proposed that the variation in air quantity can be represented by various differential equations.

They demonstrated the close correlation between experimentally derived leakage constants and theoretically predicted values for both forcing and exhausting ventilation. Similarly Metcalf (1958) obtained a volume and pressure increase ratio by dividing the length of duct into short intervals, each having an individual leakage resistance and the total length of duct having a combined leakage resistance.

The quantity of air can be determined by integrating the equation for leakage. A change in quantity due to leakage results in an immediate change in pressure. The pressure after '*n*' duct intervals can be determined by integrating this expression. Change in pressure will result in change in the quantity of leakage so a more accurate approximation for leakage is obtained.

Dzidziguri and Cholikidze (1977) proposed a method for the summation of discrete leakage paths for calculating the total air losses in long air ducts. Assuming that air leakage in the first metre length of a duct is ΔQ m^3/s, and the initial quantity of air beyond the fan is Q_0 m^3/s, then a leakage coefficient can be described as $\delta = (\Delta Q/Q_0) \times 100$ (per cent). An equation can be derived for summing air leakages over an entire duct length. Sufficient accuracy can be obtained by considering only the first five to six terms of the equation. For low values of δ (0.4–1.0 per cent) three terms are sufficient with the error incurred being less than 2.0 per cent.

Ventilation network analysis

Vutukuri (1983) proposed that analysing flow in a leaky duct is possible by assuming a number of discrete leakage paths and treating the leaky duct as a ventilation network as shown in Figure 1. A number of assumptions have been made in the following ventilation network analysis equations:

- leakage paths have some resistance and the resistance coefficient of leakage paths (R_p) is the same (all joints and other leaks are made and maintained in the same fashion)

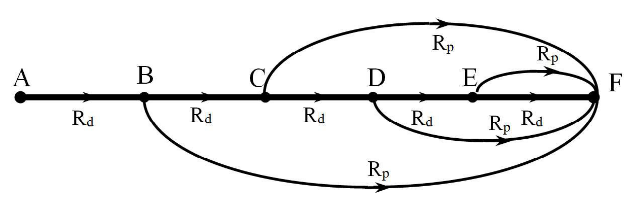

FIG 1 – Vutukuri's network analysis for leaky duct.

- the resistance coefficients of all duct sections are the same (R_d)
- the pressure outside the duct is assumed to be the same along the airway.

Using a computer program to calculate the leakage Vutukuri found that the results were within 2.0 per cent of those obtained by the method developed by Holdsworth, Pritchard and Walton (1951).

Duct leakage measurements and prediction

Gillies and Wu (1999) suggested a method of macroscopic investigation of air leakage and friction resistance of auxiliary ventilation ducting systems. Conceptual models that describe the leakage characteristics of auxiliary ventilation ducting systems were developed based on this information. Experimental methodology proposed relying on computer data acquisition has allowed the accuracy of measured values to be treated with a high degree of confidence.

Test work results confirm that ventilation ducting leakage is dependent on the ducting material, length and diameter and the pressure difference between the inside and outside of the ducting. The literature review performed identified a number of equations available for calculating the leakage and impedance of ducting. The equations for calculating leakage are complex and require a number of measurements, therefore an approximate solution was proposed and developed. The approximate equation is based on the use of a leakage coefficient that was found to be in the form of:

$$L_C = (a\,P_f)D^2 + (b\,P_f)D + c \quad (1)$$

where:

D is ducting diameter
Q_i is quantity handled by the fan
Q_o is quantity actually delivered to the face
P_f is fan static pressure in the duct
R is duct resistance
L is length of duct

Constants a and b depend on the ducting material and the quality of installation. Once these constants have been calculated for a specific type of ducting or provided by the manufacturer, an approximate solution for the leakage coefficient can be found if the fan pressure and duct diameter are known.

An approximate solution for calculating the air delivered to the face via fan and ducting system was found by converting Robert's volume increase ratio empirical equation into metric form using NBCs leakage nomogram.

$$Q_0 = \frac{Q_i}{1 + 7 \times 10^{-6} \times L_C \sqrt{R} \times l^{1.5}} \quad (2)$$

A comparison was undertaken between the equation developed in this study to find the air quantity delivered to the working face, Vutukuri's leakage prediction network analysis program and the NBCs leakage Nomogram. Vutukuri's network analysis approach is based on assigning a resistance coefficient to the leakage path analogous to the resistance of the duct and dependent on the joint construction and quality of installation. The results of this comparison exercise are set down in Figure 2.

MEASUREMENT OF DUCT LEAKAGE

Experimental methodology adopted for field ventilation duct leakage tests has been documented (Gillies and Wu, 1999; Wu and Gillies, 2014). Due to the high degree of accuracy

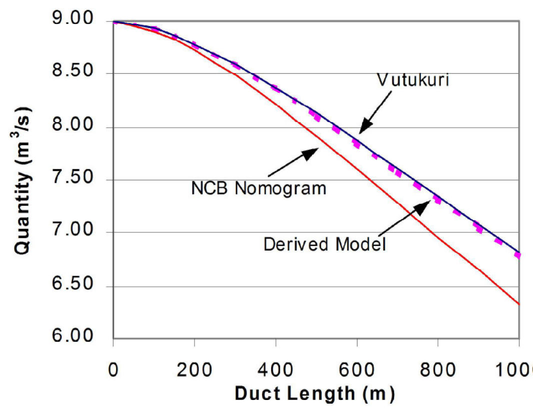

FIG 2 – Comparison of various duct leakage prediction techniques.

required and large amount of data electronic precision pressure transducers were used with a portable computer for data recording. Pitot-static tube traverses were conducted at strategic intervals along the length of the ventilation duct in order to measure the total and static pressures. From this information the velocity pressure and volumetric airflow rate through the duct at any specific location could be determined.

All tests were undertaken in the open air within the grounds of the University of Queensland Experimental Mine (UQEM). Metal clips and ropes were used to hang and support the ducting from catenary wire. The catenary wire was supported by a system of rigid metal supports set 8 to 10 m apart. Figure 3 shows a graphical representation of the location of the joints and metal pillars along the entire 80 m test length. A variable speed forward curve bladed centrifugal fan forced air along the ducting.

A Pitot-static tube connected to the pressure transducers was used to measure total and static pressures while manually recording data. Two digital pressure transducers were used. This testing package has the ability to provide direct pressure results in any engineering units. The degree of accuracy that the sampling resolution of the transducers produced increases with higher velocities. The predicted error for velocities above 8 m/s is less than 0.25 per cent.

An equal area traverse method was used to measure the quantity of airflow at a given point. Circular ducts were divided into a number of concentric areas and readings taken at the centre of each area along horizontal and vertical diameter arms. Five concentric areas were used for each cross-section traverse. The centre point of the duct was taken as a twenty first measurement point.

It was decided to take the traverses on both upstream and downstream sides of the joints. It must be noted that traverse points were not placed close to joints in order to avoid disturbance of airflow and as a consequence were located normally 5 m upstream and downstream of these locations. No measurements were possible immediately after the second joint as this section of the ducting was strung across a gully in rough ground. The quantity flowing through auxiliary

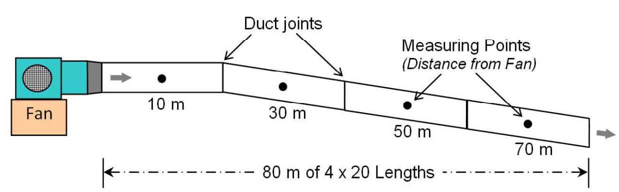

FIG 3 – Layout of the ventilation duct testing facility at UQEM.

ducting will depend upon the fan operating curve and the resistance of the system. The fan was set to operate at various speeds to obtain three different flow rates through the tested ventilation ducting system.

Once the auxiliary ducting had been hung in position, points for incisions were located. An incision was made large enough for the positioning of the Pitot-static tube but small enough to limit leakage. All static pressures measured at each measuring station were averaged and the difference between this pressure value and the atmospheric pressure measured at each station assumed to represent the static pressure for this cross-section. The following equation is given by Browning (1983) for the calculation of resistance constant of ventilation ducting.

$$R = \frac{P_1 - P_2}{L} \times \left(\frac{5}{2Q_1 + 3Q_2}\right)^2 \times 100 \quad (3)$$

where:

R is resistance constant

$P_{1;2}$ are pressures at the upstream or downstream points

$Q_{1;2}$ are airflow quantities at the P_1 or P_2 points

L is distance between upstream and downstream points

This resistance constant was then converted to Atkinson's friction factor, K, using the average air densities measured at the beginning of each measurement series. The ventilation duct was divided into a number of intervals each of which contained a different arrangement of straight section, joints and bends. This allowed the friction resistive properties of the material to be determined and equivalent friction factors for various anomalies to be determined. A standard technique to handle data processing was developed by the authors and implemented with obvious errors being eliminated and the remaining values averaged.

CHARACTERISTICS OF VENTILATION DUCTING SYSTEMS

Over the years, various types of ventilation ducting systems have been tested for their performance characteristics in term of their friction factors and leakage coefficients. The following table shows the performance characteristics of four selected ducting construction types (two welded and two sewn) of ventilation ducting systems that have been tested.

These ducting systems were tested with various duct diameter sizes which affect the leakage characteristics of the systems. The larger diameter ducting has greater leakage. Le Roux (1990) proposed that this is to be expected on account of the greater surface area of the seams and joints. Therefore it is important to convert all the leakage coefficients into ducting diameter values of interest using the leakage prediction equations derived by Gillies and Wu (1999), for example 1067 mm, and 1400 mm. Table 1 shows the converted leakage coefficients for the four ventilation ducting systems.

It should be noted that all predicted operational performances of the forcing fan and ventilation ducting systems stated in this study are derived based on the standard ventilation duct leakage test results which were carried out under a simulated mine ventilation ducting operational condition that takes into account minimum bends and kinks in the brand new ducting and with no obvious wear and tear or cut holes. Therefore when assessing the performance of a fan and ducting system installed under harsh operational condition at mines, extra bends, kinks, wear and tears or cut holes could seriously affect the performance of the fan and ducting system.

PREDICTED PERFORMANCE OF DUCTING SYSTEMS

Case study 1 – different construction types of ducts

The first case study compares predicted operating costs of auxiliary ventilation systems connecting with two different construction types of ventilation ducts. The case study consists of an auxiliary fan such as a *Clemcorp CC1400 Mk4* with twin 110 kW motors connected with either a 1400 mm diameter Type A duct as described in previous section or the same diameter Type C duct over a distance of 850 m. It is assumed that these two auxiliary ventilation systems are of a standard and straight line installation for the section near portal of a typical decline development. The auxiliary ventilation ducting systems are for a remote mining operation in Australia. Therefore, a power efficiency of 70 per cent and a typical power cost of A$0.25/kWh using diesel powered generators to provide the remote mine site power were assumed.

A friction factor, K, of 0.00221 Ns^2/m^4 and a leakage coefficient, L_C of 0.401 $m^3/s/100$ m @ standardised 1 kPa fan pressure based on the results of recent tests were used for the modelling of the auxiliary fan system with Type A duct. A friction factor, K, of 0.00337 Ns^2/m^4 and a leakage coefficient, L_C of 0.732 $m^3/s/100$ m @ standardised 1 kPa fan pressure based on the average of previously tested sewn construction ducts were used for the modelling of the Type C duct system. The following Table 2 and Figure 4 show the predicted operational performance and annual power costs of two 1400 mm auxiliary ventilation ducting systems over a distance of 850 m.

The modelling results show that predicted annual power cost savings for using the Type A (welded construction) duct over the Type C (sewn construction) duct is over A$45 980 per annum on one single auxiliary ventilation installation. With typical mine operations of 10+ fan installations, the

TABLE 1

Performance characteristics of various construction types of ventilation ducting systems tested.

Duct type	Friction factor K, Ns^2/m^4	Leakage coefficient L_c, $m^3/s/100$ m			Comments
		610 mm	*1067 mm*	*1400 mm*	
A	0.00221	0.248	0.342	0.401	Welded duct; high performance ducting
B	0.00337	0.320	0.446	0.522	Welded duct; standard performance ducting
C	0.00337	0.478	0.625	0.732	A durable material from a single length of material joined by a single line of stitching at the top attachment flange
D	0.00254	0.570	0.745	0.873	A lightweight material with length of material joined by a single line of stitching at the top attachment flange

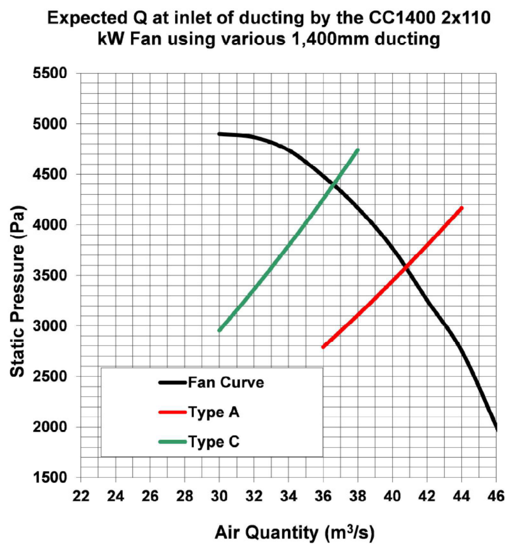

FIG 4 – Expected fan operating points of Duct A and Duct C under the case study condition.

potential power cost savings could be several hundred thousand dollars. Also more importantly that the system using Type A duct is able to deliver more air (extra 24 per cent or 7.2 m^3/s) at face using the same fan when compared to the auxiliary ventilation system using the Type C duct.

As a welded, low resistance and low leakage type ducting, Type A duct is able to deliver more air to workings when compared with the typical sewn type ducting such as Type C duct. With more air delivered it provides a greater degree of safety for employees in underground working areas. Some advantages of using ducting with lower friction factor and less leakage include the following:

- increased air delivery – welded type ducting such as Type A duct with less leakage is able to deliver more air to faces when compared with the typical sewn type ducting
- safer working conditions – with more air delivered to the workings, it provides a greater degree of safety for employees in working areas and can reduce exposure levels of harmful airborne contaminants in underground mining environments
- higher mine productivity – it will also reduce after blast re-entry times and supports quicker mine development rates hence higher mine productivity
- reduced power consumption – low leakage, low resistance welded ducting is more energy efficient, and reduces wastage of the highest operating cost component of ventilation ie power
- reduced heat loads – welded type ducting with less frictional and leakage loss requires less fan energy (less heat) to deliver more air (more cooling power) hence increased air cooling power of the ventilation system to workings and resulting less mine heat load overall
- savings of capital and operating costs – use of welded type ducting has potential savings both on capital and operating cost of auxiliary ventilation fan as smaller fan could be used to deliver the same amount of fresh air at face that is delivered by a typical sewn construction ducting
- aligned with best practices – it is aligned with best practices globally for delivering more air, and reducing power wastage, a significant but often intangible cost at mining operations.

Case study 2 – effects of duct fittings

For evaluating the performance of ventilation ducting systems, it is important to know that whenever the ventilation airflow is required to change direction, additional vortices will be initiated. The propagation of those eddies consumes mechanical energy (shock losses) and, hence, the resistance of the airway may increase significantly. This occurs at bends, junctions, changes in cross-section, obstructions, regulators and at points of entry or exit from the system. As part of the study, it also assesses the technical importance of streamlined design (low aerodynamic resistance) to reduce the shock losses of the duct fittings.

The purpose of the second case study is to compare the predicted energy consumption scenarios of two ventilation ducting systems, one connected with conventional single mitre elbow pieces and the other utilising four-segment lobster-back elbow pieces with gentle radius curve design as shown in the Figure 5. Predicted performances of these two ventilation ducting systems are based on test results at UQEM and shock factor calculations from *Wood's Practical Guide to Fan Engineering*, 1992. The study assumed the four-segment lobster-back 90° bend is equivalent to the 'plain radius' bend with the radius of 5.66 m. So the ratio of radius to diameter is 4:1. Therefore, shock factor for the lobster-back bend is calculated at 0.17 and shock factor for the single mitre 90° elbow is 1.12.

The case study consists of an auxiliary fan such as a *Clemcorp CC1400 Mk4* with twin 110 kW motors connected with a 1400 mm diameter Type A duct with three sets of 90° four-segment lobster-back elbow pieces or with three sets of conventional 90° single mitre elbow pieces under the assumption of a new standard ducting installation with no obvious wear and tear. The case study represents a typical auxiliary ventilation system used for development sublevels with the fan placed at points near the fresh air sources. A friction factor, K, of 0.00221 Ns^2/m^4 and a leakage coefficient, L_C of 0.401 $m^3/s/100$ m @ standardised 1 kPa fan pressure were used for the modelling and calculations. The following

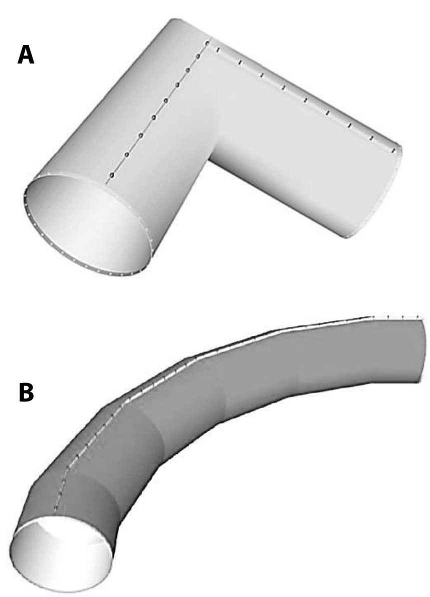

FIG 5 – (A) 90 degree single mitre piece and (B) 4 segment lobster-back elbow piece

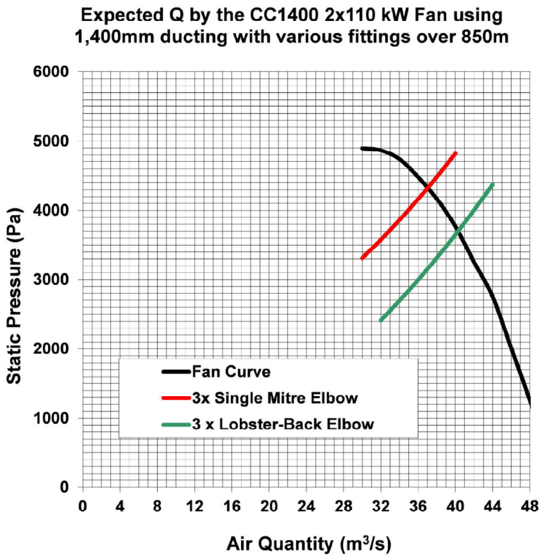

FIG 6 – Expected fan operating points of Duct A with the two types of fittings under the case study condition.

Table 3 and Figure 6 show the predicted performance of two ventilation ducting systems over 850 m.

The modelling results show that predicted annual power cost savings for the ducting system with streamline design fittings as compared with conventional duct fittings is in excess of A$26 200 per annum on one single fan installation. With typical mine operations of ten or more fan installations, potential power cost savings could be several hundred thousand dollars. The ducting system with four-segment lobster-back elbow pieces is able to deliver an extra 11 per cent (36.4 m^3/s versus 32.8 m^3/s) of fresh air at face when compared with the system with conventional single mitre elbow fitting pieces.

The ventilation ducting system using high flow, low aerodynamic resistance fittings such as four-segment lobster-back elbow is able to deliver more air to workings when compared with ducting fitted with the conventional single mitre elbow pieces. Advantages of using ducting fitted with low aerodynamic resistance design duct fitting pieces are summarised as follows:

- reduce overall ducting system resistance
- reduced power consumption
- increased air delivery
- reduced heat loads
- safer working conditions
- savings of capital and operating costs
- higher mine productivity
- aligned with best practices.

CONCLUSIONS

The objective of this paper is to examine some modern forms of auxiliary ventilation fabric ducting with streamline design fittings and the efficiency of construction practices. The most dynamic form of auxiliary ventilation is a moveable fan and ducting which is easy to install especially with the use of light weight fabric. The porous nature of some ducting construction results in leakage and loss of efficiency.

Mathematical modelling has been undertaken to predict the performance of auxiliary ducting ventilation ducting systems by providing some indications of differences in ventilation flows to the mining face. Performance information sought are resulting fan pressure, leakage loss and the air flows at the outlets of the ducting. Excel spreadsheet and computer modelling have been used to establish the predicted performances of the forcing fan and ducting systems considered.

Forcing auxiliary ventilation systems employing circular fabric ducting have been examined. Leakage of air from ducting is affected by ducting material and construction methodology (such as welded or sewn), quality of installation, number of joints, total length, pressure differences between the inside and outside and diameter. The best ducting system with welded construction can have up to four times less leakage as compared with some systems with sewn construction. It is also evident that the sewn type ducting will deliver less air

TABLE 2

Predicted annual power costs for Duct A and Duct C ventilation ducting systems.

Ducting type	Ducting length	Air Q inlet	Fan pressure	Air Q @ face	Unit power cost	Power efficiency	Predicted annual power cost
	m	m^3/s	Pa	m^3/s	A$/kWh	%	A$
Type A duct 1400 mm	850	40.8	3582	37.0	$0.25	70%	$456 256
Type C duct 1400 mm	850	36.6	4395	29.8			$502 237

TABLE 3

Predicted annual power costs for Duct A ventilation ducting systems with different fittings.

Type A duct	Duct fittings		Air Q inlet	Fan pressure	Fan power	Predicted annual power cost
	Shock factor	Shock loss				
	dimensionless	Pa	m^3/s	Pa	kW	A$
With 3 × lobster-back elbow bends	0.17	210	40.2	3686	218	$476 439
With 3 × single mitre elbow bends	1.12	1375	37.0	4320	230	$502 665

to working faces and require more fan power, hence higher operating costs to run when connected to the same fan.

A case study has also been undertaken to compare predicted operating costs of auxiliary ventilation systems connecting various types of ventilation duct fittings. The study also assesses the technical importance of streamline design with low aerodynamic resistance to reduce the shock losses of the duct fittings. It was found that the system connected with streamlined design fittings is able to provide some power cost savings and deliver more air compared with the system fitted with conventional fitting pieces.

Using a ventilation ducting system with a lower leakage and frictional characteristic will result in a direct saving on fan operating cost compared with a flexible ventilation ducting system with a standard or higher leakage coefficient. Using a ventilation ducting system of a lower leakage coefficient and low resistance with the same kW rated fan will supply more airflow to the mine face as the system has less leakage. Other savings or advantages associated with the use of such a system include:

- potential saving both on capital and operating cost of auxiliary ventilation fan as smaller fan can be used
- provision of a safer working environment that complies with mine health and safety regulations especially for higher production.

Using a ventilation ducting system with a lower leakage and frictional characteristic represents a sound solution to new challenges faced by the industry for increasing demands for better quantities and qualities of air delivered to working faces due to higher production schedules and stricter mine health and safety regulations within the Australian mining industry.

It should be noted that all predicted operational performances of the forcing fan and ventilation ducting systems stated in this study were derived based on the standard ventilation duct leakage test results which were carried out under a simulated mine ventilation ducting operational condition that takes into account minimum bends and kinks in the brand new ducting and with no obvious wear and tear or cut holes. Harsh operational mine condition where, extra bends, kinks, wear and tear or cut holes may occur are all too common. When assessing the performance of a fan and ducting system it is important to recognise the serious effects these can have on the performance of a fan and ducting system.

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REFERENCES

Browning, E J, 1983. An approximate method for auxiliary ventilation calculations, *Mining Engineer*, 264–9 (*Trans. Instn. Min. Engrs,* 143).

Dzidziguri, A A and Cholikidze, G V, 1977. Calculation of the total air losses in long air ducts, *Soviet Mining Science*, 13–5.

Gillies, A D S and Wu, H W, 1999. A comparison of air leakage prediction techniques for auxiliary ventilation ducting systems, in *Proceedings Eighth US Mine Ventilation Symposium* (ed: J Tien), pp 681–690 (University of Missouri-Rolla Press: Missouri).

Holdsworth, J F, Pritchard, M A and Walton, W H, 1951. Fluid flow in ducts with a uniformly distributed leakage, *British Journal of Applied Physics*, 2–11.

Le Roux, W L, 1979. *Mine Ventilation Notes for Beginners,* third edition (Mine Ventilation Society of South Africa: Johannesburg).

Le Roux, W L, 1990. *Le Roux's Notes on Mine Environmental Control,* fourth edition (Mine Ventilation Society of South Africa: Johannesburg).

Metcalf, J R, 1958. Leakage in ventilation tubing, *Mining Magazine*, 98–5.

Roberts, A, 1960. Booster and auxiliary fans, in *Mine Ventilation* (ed: A Roberts) (Cleaver-Hume Press Ltd: London).

Robertson, R and Wharton, P B, 1980. Auxiliary ventilation systems – planning and application, in *Proc. Commission of the European Communities Information Symp (*Colliery Guardian: Surrey).

Vutukuri, V.S. 1983. Air leakage in ventilation ducting and the design of auxiliary ventilation systems, *The Mining Engineer*, 262–7 (Trans. Instn. Min. Engrs, 143).

Wu, H W and Gillies, A D S, 2014. A comparison of predicted performance of auxiliary ventilation ducting systems, in *Proceedings Tenth International Mine Ventilation Congress* (ed: F Von Glehn), pp 533–540 (Mine Ventilation Society of South Africa).