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Verification and calibration of ventilation network models

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ABSTRACT: There is no doubt that simulated ventilation networks must be adequately verified before they can be extrapolated and used for predictive purposes. There are two general approaches as to how the verification can be established and these are summarised as follows; The first approach is to measure all individual branches with trailing hoses or barometers to get individual pressure drop and flow per branch and then calculate individual resistance factors for input into the software. The simulator is run, checking that the output makes general sense (check some sensitivities if possible). The network is now considered as verified. The pressure drop to be measured is relatively small and thus it is inherent that the measured set of individual K factors will be imprecise no matter how much care is taken in the measurements and the resultant simulations will inherit the same problem. In the second approach, the network is assembled using estimated (Atkinson) K factors (based on physical features of airway, past experience and catalogued typical K factors). Only the main primary flow rates are measured and hence the relative distribution of the primary ventilation in the main airways is determined (probably about 10 off primary air flow measurements). Main critical pressure differentials at main and booster fans and across critical doors are measured (probably about 6 off primary pressure differential measurements need to be made). The simulator is run and the computer model is used to iterate and select an updated suite of K factors so that the flow balances and pressure differentials are correctly simulated (typically only 2 or 3 iterations are all that is needed). The network is now considered as verified. The pressure differences to be measured will be substantial in absolute terms and can be measured with high precision. Also, because only primary flows are measured, these will generally be measured at higher air speed points and hence improved relative accuracy. This leads to more accurate simulation results. This paper examines the advantages and disadvantages of the two approaches.

1 Background

There is no doubt that simulated ventilation networks must be adequately verified before they can be extrapolated and used for predictive purposes. There are two general approaches as to how the verification can be established and these are summarised as follows:

1.1 Approach A

- Measure all individual branches with trailing hoses or barometers to get individual pressure drop and flow per branch, see for example, McPherson, 1993, Hemp, 1989.
- Calculate individual ('measured') R factors to input into software and hence use in network.
- Run the network, check it makes general sense (check some sensitivities if possible) and consider the network as verified.

1.2 Approach B

- Assemble the network using estimated (Atkinson) K factors (based on physical features of airway, past experience and catalogued typical K factors).
- Measure the main primary flow rates and hence the relative distribution of the primary ventilation in the main airways (probably about 10 off primary air flow measurements).
- Measure the main critical pressure differentials at main and booster fans and across critical doors (these are substantial pressure differences and can be measured with more precision, probably about 6 off primary pressure differential measurements need to be made).
- The network is run and then the computer model is used to iterate and select an updated suite of K factors so that the flow balances and pressure differentials are correctly simulated (typically only 2 or 3 iterations are all that is needed).
- Run the network, check it makes general sense (check some sensitivities if possible) and consider the network as verified.

1.3 Difference Between R Factors and K Factors

The Atkinson K factor is defined by the physical geometrical features of the airway. An airway at 200 m depth below surface in the Peruvian Andes will have the same K factor as an identical airway at 3 500 m depth in a South African gold mine. The R factor incorporates the density effects of the air and is site-specific and this factor changes by almost 100% in the above example for identical airways.

2 Ventilation Network Software

As air flows though the mine it picks up heat from the rock and machinery and in addition the temperature changes as a result of autocompression. This temperature difference at different elevations creates a natural ventilation flow through the mine.

Most available ventilation network programs treat the air in a mine as an incompressible fluid. This disables the solution algorithms from taking account of the effect of density and temperature changes in deep mines. The measurement of individual R factors by measurement of pressure and flow at all branches, is one way to partially correct for the computation deficiency of not automatically accounting for density variations. It is for this reason that individual branch measurements are more relevant when using these software tools and one of the reasons (apart from those historical) that the individual branch survey approach is often part of the procedure.

VUMA-network (Bluhm et al, 2001) is one of the few network programs available that automatically takes account of density (and heat variations) throughout any mine network. Hence only the pure K factors are of relevance. VUMA-network is an application for the full thermodynamic simulation of steady-state environmental conditions encountered in underground mines. Mine networks are constructed, managed and edited in a graphical user interactive environment. Results are viewed in full colour, fully rotational 3D graphics. VUMA-network is used to predict airflow, pollutant (dust, gas, radon, smoke, heat) and temperature distribution throughout the ventilation circuit and cooling network. The aerodynamic, pollutant, thermodynamic and psychrometric calculations are all done simultaneously and completely interactively. VUMA-network represents a very significant and unique knowledge base and all the algorithms used have been verified in recent work and over a development period of some two decades.

For the normal operation of VUMA-network, the user only has to specify the inlet temperature (usually surface) and the calculation algorithms will determine air temperatures throughout the network. The user then compares the predicted temperatures with underground measurements and, if necessary, adjusts branch input parameters in order to 'calibrate' the predictions and ensure confidence in predictions for future expansions to the mine.

2.1 Automatic Determination of NVP

The determination of NVP (natural ventilation pressure) is an inherent feature of VUMA-network. The barometric pressure at each node is determined from the depth and the wet- and dry-bulb temperatures. Node temperatures are a function of the heat input into a branch (from conduction in the rock, auto compression and artificial heat sources such as hot and cold water pipes, electrical cables, mobile equipment). This enables the node density to be calculated. For branches in which an elevation change takes place, a natural ventilation effect in that branch will be experienced by the air based on the difference in the density and elevation. The network balancing algorithms automatically take these branch NVP effects into account and resultant fan pressures include the overall system NVP.

3 Comparison of The Two Approaches

3.1 Effective Use of Computational Power

Approach A is traditional and old-fashioned – this type of procedure arose before the advent of user-friendly powerful computing. In Approach B, the computer identifies and defines the correct suite of K factors so that the flow balances and pressure differentials are correctly mimicked. Approach B is more elegant and uses computing power more effectively.

The iteration of the K factors is done manually at present and this keeps the user closer to reality.

3.2 Inherent Measurement Precision and Mathematical Accuracy

Consider an airway of 20 m^2, 500 m long, average density 1.07 kg/m^3 in which flow and pressure drop are measured as 100 m^3/s and 100 Pa respectively - the Atkinson K factor is then calculated as 0.01. The accuracy in measuring the 100 Pa differential will never be high - it is suggested that this will not be better than +-20 Pa (which is 2mm or 0.079" water gauge). Even if the instrument specification quotes higher precision, the physical set-up does not allow it (movement of an observer will have this effect). Furthermore, assume the error in measuring the flow is +-10% (which, based on general experience, is typical to good). The inherent measurement error or confidence level in calculating the individual K factor will range between 0.0066 and 0.01. This confidence range can also be determined differentially using error analysis techniques as:

$$\partial K/K = \partial P/P + 2 \,.\, \partial Q/Q = 20\% + 2 \,.\, 10\% = 40\%$$

Thus in Approach A, it is inherent that the measured set of individual K factors will be imprecise no matter how much care is taken in the measurements and the resultant simulations will inherit the same problem.

In Approach B, the pressure differences to be measured will be much higher in absolute terms and these can be measured with much better relative accuracy. They would typically be 3000 Pa (300 mm water gauge) and sometimes much higher than this. Also, the air flows will generally be measured at higher air speed points and hence with improved relative accuracy.

Indeed if given the sole task of accurately determining the K factor of a particular airway, the approach proposed is to evaluate its effect on the network via Approach B and thus define it at a higher level of precision – rather than attempting to measure it directly.

The network modelling and the deductions that can be drawn are often more accurate than individual measurements. The authors have used VUMA very successfully to explain issues like:

- There has to be leakage in a certain part of the mine (or it does not make sense) - then go and look for it and find exactly what was expected.
- There has to have been a fall-of-ground or some other blockage in a certain part of the mine (or it does not make sense) - then go and look for it and find exactly what was expected.

Mathematically, the network behaviour method of evaluating K factors is inherently more accurate - because of all the numerous parallel paths and semi-parallel paths that all affect each other and the 'damping' effect that this has on variations in pressure and flow.

4 Case Studies

Approach B has been used successfully in the analysis of many mine ventilation systems and the results of two case studies are presented here.

4.1 Coal Mine

As part of a broader study to optimize the mine ventilation system at Bank Colliery, VUMA-network was used to model the mine and to evaluate correlation with operational data (Belle and Marx, 2002).

The following methodology was applied in the study:

- Obtain mine ventilation network layout, and the required physical and operational data.
- Construct the simulation model and complete data input.
- Obtain base case solution and ensure correlation with operational data.
- Evaluate results and optimize airflow distribution through 'what-if'' analysis.

The following figures are graphical representations of the simulation model that was developed in VUMA-network. Figure 1 shows a geometric view of the underground ventilation network and Figure 2 shows a three-dimensional view.

Table 1 shows the correlation obtained between the base case simulation and the operational data for the main intake and return system of the mine using 'standard' Atkinson-K factors for the different roadway types:

Table 1: Intake/return airflow balance.

Position	**Measured m³/s**	**Predicted m³/s**
SW1 Downcast	102.8	105.6
Belt Incline Downcast	43.2	44.9
Transport Incline Downcast	157.4	147.8
SE28/ Downcast	44.9	46.1
Rescue Borehole Upcast	2.8	5.1
Up-cast - South Shaft Fan	215.0	214.2
Up-cast – Fan 5	136.7	136.8

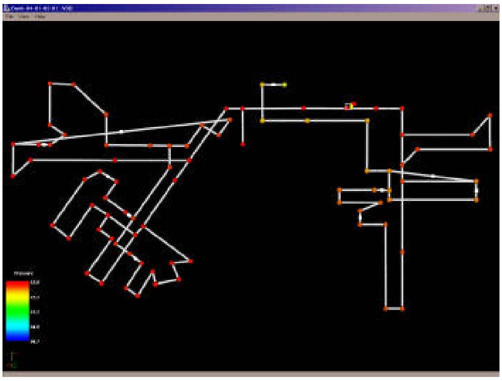

Figure 1. Geometric view of the South shaft ventilation network

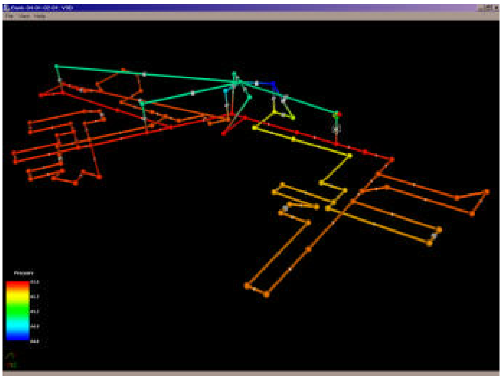

Figure 2. Three-dimensional view of the South shaft ventilation network.

The network was 'calibrated' by altering the Atkinson-K factors in those branches where the predicted and measured flows differed significantly.

4.2 Deep Gold Mine

The flowing results were obtained during a study on a deep South African gold mine. The objective of the study was to assist with calibrating heat and flow parameters and to establish a platform for future scenario planning. The mine extends 3400 m below surface and has a down-cast air flow of about 650 m³/s. A three-dimensional view of the network is shown in Figure 3.

Initial results obtained using standard Atkinson–K factors for the different airway types are shown Table 2. Although there are generally larger differences in cross cuts with low air flow, it should be noted that measurement accuracy is typically within 15 percent and lower air flow rates in cross-cuts are dynamically influenced by vehicle movement and by ventilation doors being opened and closed.

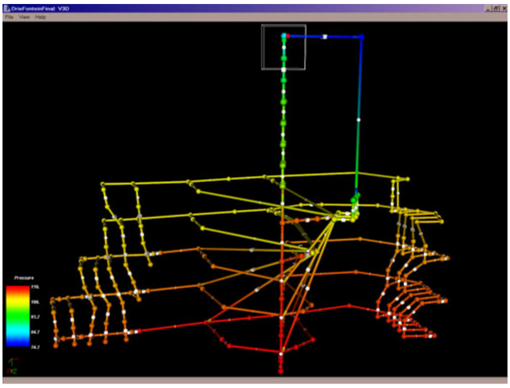

Figure 3. Three-dimensional view of the main shaft ventilation network.

Table 2: Comparison of measured vs. predicted flows using standard Atkinson-K factors

Main intake Level	Cross-cut No.	Measured flow m³/s	Predicted flow m³/s
46	21	5.5	7.9
46	22	15.0	15.3
46	23	18.8	18.9
46	24	13.6	10.0
46	25	9.6	9.5
48	21	2.2	1.0
48	22	5.1	7.1
48	23	8.5	5.6
48	24	2.3	4.8
48	25	10.9	8.7
50	21	5.5	6.8
50	22	11.5	11.5
50	23	16.5	16.0
50	24	14.8	14.1
50	25	9.3	9.5

The study indicated that standard Atkinson-K factors need to differentiate between producing stopes, mined out raises and ledging stopes which are still only centre raises. However, it is not necessary to carry out surveys to identify these K factors but the simulation software can be used to determine new 'standard' values for different scenarios.

5 Monitoring and Control

Effective monitoring of underground environmental conditions is becoming accessible to mine operators, with improved instrumentation and communication systems, see for example, Mutama and Meyer, 2006. However, the multiplicity of ventilation branches and equipment, as well as the numerous ventilation parameters of interest, make it impractical to locate measurement transducers all over a mine. Those systems that attempt to do so, generally become too large and complex and are often unreliable, lack credibility and are ultimately ineffective. Furthermore, the actual transducers for ventilation parameters are notoriously difficult to maintain (for example, air flow and wet-bulb temperature sensors). The installation of many of these transducers all over a mine network is very expensive in first cost and can only be effective with high maintenance efforts. Older mines with a limited life expectancy would not be able to justify the expense of an extensive communication and environmental monitoring system. In most mines these systems are generally doomed to unreliability. Even with a large budget, there will inevitably be areas in a mine that lack instrumentation. It is more practical to have a few critical measurement sites that are fully reliable and, from these critical measurements, extrapolate conditions all over a mine network using ventilation network software. The VUMA-network simulation software includes a feature that enables confident predictions of mine-wide conditions to be made on the basis of a limited number of monitored parameters (von Glehn and Ox, 2004). This monitoring system has been called VUMA-live. The system is currently being installed in a gold mine to verify the link between the mine SCADA system (with instruments mainly in the primary intake circuit) and the network file. Data from measurement stations close to the workings will be incorporated in future to allow rules on reasons why there may be differences between predicted and measured parameters to be tested – a form of self-teaching. These rules will allow not only the locations of problem areas to be identified, but also the possible cause.

With strategic placement of sensors, VUMA-live can be used to assist the active control of ventilation systems. The system could identify whether operators are correctly switching fans when they enter/leave an area (if status of fans in operating stopes is monitored), and it would be able to continuously assess whether sufficient air is being supplied to working places. A central control station would be alerted whenever conditions do not satisfy minimum requirements.

If the program is linked to a central vehicle despatch system, it would ensure that sufficient air follows equipment as it moves through the mine. VUMA-live could instruct the SCADA system to manipulate fans/regulators and indicate whether equipment is allowed to move to certain locations.

6 Conclusions

The capability of modern ventilation network simulation software needs to be exploited to obtain accurate predictions of future mine networks. In order to obtain an accurate correspondence between operational air flows and those predicted by software it is not necessary to carry out a detailed ventilation survey in each branch of the mine. It is possible to measure only a few strategic parameters and to calibrate input data to ensure that the simulator accurately predicts values in the rest of the circuit. The calibrated network can then be used confidently to examine future scenarios.

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