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ANALYSIS OF FRICTION FACTORS IN MINE VENTILATION SYSTEMS

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Analysis of friction factors in mine ventilation systems

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ABSTRACT: A program of field measurement work to determine airway friction factors was carried out in underground Canadian Mines. The work was confined to straight, unobstructed lengths and included steel arched gangways, and gunited surfaces as well as raw rock airways. Standard techniques were employed for airflow and pressure drop measurements and a photoprofiling method was used to characterize the airways. The results obtained in the igneous rock sites were generally lower than those in the well-known standard table of airway friction factors, reflecting the larger size and smoother conditions in the modern airways. The hydraulic surface roughness values for airways were calculated using the basic Darcy equation for duct flows. The friction factor of airways with different dimensions can be predicted if the roughness value is known.

1 INTRODUCTION

In the design of an underground mine ventilation system, the first step is to determine the volume of airflow required in all parts of the mine. A number of factors are involved in this determination such as quantities of dust and noxious gases to be diluted to safe levels, provision of adequate oxygen levels and maintenance of a comfortable temperature range. Once the flow distribution has been determined, it is necessary to estimate the pressure required to force these air quantities through the respective mine openings for the selection and placement of fans and other ventilation controls.

The principles underlying the accepted theory of mine ventilation were put forward by J.J. Atkinson in 1854. In its simplest form, Atkinson's equation states that the pressure drop in a mine airway is proportional to the square of the volume of air flowing, the constant of proportionality being defined as the resistance of the airway, or: -

$$P = RQ^2 \qquad (1)$$

where P is the pressure drop, R is the resistance, and Q the airflow rate.

The airway resistance, R, depends on the dimensions of the airway and the nature of the rubbing surface, such that:

$$R = KCL/A^3 \qquad (2)$$

where K is regarded as a friction factor characterizing the roughness of the rock surface, L is the length of the airway, C is the perimeter of the airway cross section, and A is the cross-sectional area. The dimensional parameters are readily determined but some judgement is required in the selection of K.

Many mining companies measure representative K-factors for their own internal use but, for planning purposes, the most widely used reference source dates back to a series of carefully conducted measurements carried out in the mid 1920's (McElroy & Richardson 1927). Measurements of K-factors carried out in modern mine openings have generally indicated values lower than those of the 1920's, particularly for the case of airways in igneous rock. This is understandable considering the mine openings in which the original work was done. Photographs of these airways show that they were mostly between 2 and 2.5 m in diameter, with extremely rough rock surfaces. Modern mine openings, particularly in trackless mining zones, are generally much larger, and modern drilling and blasting techniques generally produce smoother walls. The relative roughness is thus reduced and, since modern hydraulic theory shows that for fully turbulent flow the friction factor is purely a function of relative roughness of the conduit, we should expect lower values of the K-factor.

There is, therefore, a need to produce a table of airway friction factors more applicable to modern mining conditions. This need is augmented by the increasing trend to the use of computer network programs to solve mine ventilation problems. Accurate resistance values for each branch of the network are required for the basic data set for such programs.

Examination of equations (1) and (2) shows that the value of the K-factor, as used in mine ventilation work, depends on the units chosen for length, pressure, and airflow rate. In the SI system, with lengths in m, pressure in Pa, and flow rates in m^3/s, the K-factor has units of Ns^2/m^4, or kg/m^3 (i.e., units of density).

In other unit systems, K contains various unit conversion factors depending on the pressure and flow units used. Thus, K takes different values in different systems.

It has become customary, in mine ventilation work, to include standard air density in the K-factor and apply corrections to calculated pressure drops according to the actual air density in the mine. When using SI units, however, a case can be made for separating the density term from the K-factor, making the latter dimensionless.

The Darcy equation for head loss caused by the friction in long, straight, uniform ducts is given by

$$H_f = fLV^2/2gD \tag{3}$$

where f is the dimensionless hydraulic friction factor, L is the length of the duct, D is the hydraulic diameter (4 A/C), V is the velocity, and g is the acceleration due to gravity. This equation is applicable for all units, as long as the quantities are consistently expressed.

The equation (3) is valid for a duct of any shape of cross section and applies for either laminar or turbulent flows. In general, the value of the hydraulic friction factor, f, is a function of Reynolds number and the relative roughness, e/D. The roughness, e, is a length characterizing the hydraulically effective roughness of any duct surface and can be derived experimentally. The results of tests (Nikuradse 1933) on turbulent flow in rough ducts has shown that at high Reynolds numbers, the value of f of rough ducts becomes constant, depending wholly upon the roughness of the duct surface and is thus independent of the Reynolds number. The relationship between f and e/D is expressed by

$$f = 1/[2 \log (3.7 D/e)]^2, \; D = 4A/C. \tag{4}$$

The dimensional comparison of the Atkinson and Darcy equations shows that

$$K = 0.125 f. \tag{5}$$

Since airflow in mines is usually well into the turbulent range, this is a means of calculating K-factors from airway dimensions and an assessment of surface roughness.

The roughness value, e, for an airway can be determined from the following equation.

$$e = 14.8 A/C \operatorname{Alog} (1/\sqrt{32K}) \tag{6}$$

The advantage of this equation is that once the roughness value is known for an airway, the K-factor for similar types of airways, but with different cross sections, can be determined using equations (4) and (5).

In this study, all measurements and calculations were carried out in SI units. These units are very convenient for mine ventilation work and are becoming well established in the mining industry. Friction factor and roughness values were determined for straight unobstructed airways only. No attempt was made to assess shock factors due to bends, contractions or other obstructions.

2 TEST METHODS

In principle, the determination of mine airway K-factors is quite simple. Using equation (1), the resistance of an airway can be calculated from a measurement of the pressure drop associated with a measured flow rate. From this resistance value and the relevant airway dimensions, the K-factor can be calculated using equation (2).

In practice, of course, the process is much more difficult due to the irregularity of the airways, fluctuations in airflow rate and the practical difficulties associated with measuring flow rates and pressure drops to the required degree of accuracy.

2.1 Selection of representative airway

The first pre-requisite is the selection of a representative length of airway.

Since the objective is to characterize the frictional nature of the airway surface, the airway chosen must be as uniform in nature as possible throughout its length. To avoid the masking influence of shock factors, it should be reasonably straight and unobstructed. Ideally, the longer the airway the more accurately the pressure drop can be measured.

The accuracy of both pressure drop and flow rate measurements is improved at higher velocities of airflow. A minimum velocity of 3 m/s should be sought. In some cases it may be possible to arrange to have more airflow temporarily diverted to the survey section for the purposes of the measurements. Measuring pressure drops at two or more different flow rates gives a useful check on the results.

2.2 Preparation of test section

The length over which the pressure drop was to be determined was accurately measured with a tape, and the ends marked on the wall with a paint spray can. The perimeter and area were recorded at regular intervals along the section using a photoprofile technique described in the next section. Representative photographs were also taken to illustrate the general nature and condition of the airway.

Two suitable locations for airflow measurement were selected, marked, and photoprofiled for each airway. Where possible, the flow measuring stations were selected outside the test section to cause minimum interference with the pressure drop measurement.

2.3 Cross section measurement

In airways of irregular area the airflow does not occupy the total area. The total area measurement may lead to some errors in the calculations. In theory, the effective area through which air actually flows should be used rather than the total area of the sections. However, in practice it is difficult to measure the effective areas of the sections. In this work the airway dimensions were measured at various locations in test section using the photoprofile method to reduce the error due to inaccurate estimations of effective areas. The average of airway dimensions measured at various locations in the test section was used in all the calculations. The most important effect on the K-factor is that of area determination, and areas and perimeters are calculated from the same data. The errors in such data will involve an error in the friction factors proportional to A^3/C. For example, a 10% increase in area and a 5% increase in perimeter will increase the value of K by about 27%.

The measurement of areas and parameters in this work were conducted by a photographic method devised previously by the Mining Department of Queen's University. In principle this involves the projection of a narrow band of light to illuminate the perimeter of an airway on a plane perpendicular to the airway axis. A polaroid camera is then used to photograph the illuminated band. A scale of known length is also illuminated in the plane of the profile to relate the dimensions of the photograph to field dimensions. Perimeters and areas were determined from the photographs by a simple computer program after tracing the outline and scale by means of a digitizer.

To illustrate the variability of the airways, composite plots were made of the digitized profiles for each test section. A small computer program was written to find the coordinate centre of each section, adjust all sections to the same scale, and plot the super-imposed profiles at a convenient size together with an appropriate scale bar. Typical cross sections of airways are shown in Fig. 1.

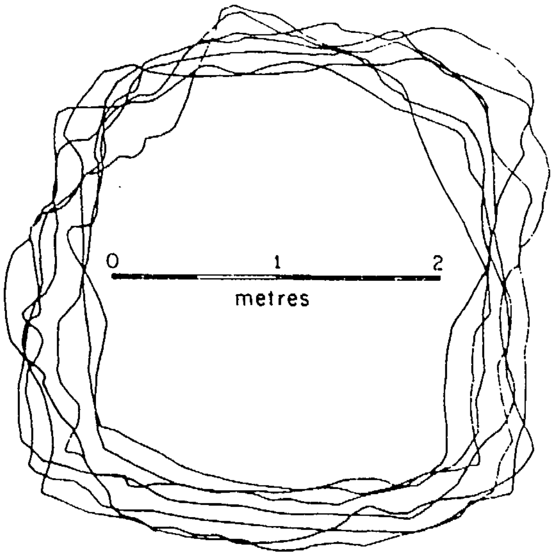

Fig. 1 - Typical cross sections of airways.

2.4 Airflow measurement

Air flow rate is not measured directly but is determined as the product of velocity and cross-sectional area, each of which is measured separately. The area measurement has already been discussed.

There are several methods of measuring air velocity and, since the velocity is not constant across the full cross-section, a technique must be used which gives a satisfactory average. The standard rotating vane anemometer is commonly used for routine mine ventilation work, and, although it is subject to large errors if carelessly used, by observing proper procedures a good average velocity can be obtained.

Since the velocity tends to be lower near the walls than in the centre of the airway, it is important to attempt to sample the airflow over the full cross-section so that the measurement represents a weighted average velocity. This is sometimes achieved by traversing the anemometer slowly in a zigzag fashion over the area. The problem with this technique is that the operator has to move around to cover the full area and this affects the air currents. If extension rods are used to enable the operator to reach the far corners of the airway from one location, then they get in the way when trying to cover the closer parts.

The preferred technique is to hold the anemometer for equal lengths of time at a number of positions, each of which represents an equal area of the airway, using extension rods where necessary, and keeping the body out of the airstream if possible.

The latter technique is more conveniently used with the second type of anemometer, namely the Electronic Direct Reading anemometer. This instrument also has a rotating vane, and is equipped with a power supply and associated circuitry which enables it to respond to the rate of rotation of the vanes so that it gives a continuous reading of velocity. Besides being more suitable for measuring velocity at selected points, this instrument is useful for observing the actual variations of velocity over the cross-section and monitoring the stability of the airflow over time. Both of these types of anemometer were used at independent stations for each test airway.

2.5 Pressure drop measurement

There are two methods of measuring pressure drop over a length of mine airway; the barometric method and the gauge and tube method. The barometric method is favoured for complete mine resistance surveys where points may be widely separated. The gauge and tube method, which measures pressure drop directly, is inherently more accurate than the barometric method and was used in this study. In operation, a length of rubber tubing is stretched out along the axis of the airway and connected at one end to one limb of a sensitive pressure difference measuring device. A length of tubing is connected to the other limb of the pressure gauge.

An electronic micromanometer was used for the measurement of differential pressures, except in the coal mines, where a magnehelic gauge was used.

The air flowing through the airway between the ends of the tubing suffers a loss of total pressure due to friction while the air in the tube is stationary. If the open ends of the tubing are pointed upstream at positions of mean velocity in the cross-section of the airway, the total pressure difference between the ends of the tube will be registered by the gauge. In practice, it is often difficult to select a point of mean velocity and it is more convenient to use a static tip at the ends of the tubes so that the gauge registers the difference in static pressure between the ends of the tube. For this survey, a pitot tube was mounted on a tripod and pointed upstream at the centre of the airway at each end of the test section. The static connections of the pitot tubes were connected to the manometer tubing. Since, for this work with uniform cross-sections of airway, the air velocity was approximately the same at both ends, the difference in static pressure was assumed to be the same as the difference in total pressure.

2.6 Air density

In order to adjust the measured K-factors to common terms, either in dimensionless form or at standard density, it is necessary to know the air density at which the pressure drop measurements are made.

K-factor values calculated from equations (1) and (2) using measured P and Q values must be adjusted by a factor of 1.2/d for SI units, or by a factor of 1/d for dimensionless units, where d is the measured density in kg/m^3.

Air density was determined from barometric pressure, and wet and dry bulb temperature readings, using standard psychrometric formulae. For this purpose, the barometric pressure need not be as accurately determined as the pressure difference measurement.

2.7 Procedure

Before making any measurements, the proposed test location by the mine official was visited to assess the suitability of the site. It was desired to have a reasonable straight, uniform airway, at least 150 m in length, and with a minimum air velocity of 3 m/s. In many cases, it was found impossible to meet all of the desired conditions at any one site. A shorter section could be tolerated if the velocity was high, and conversely, a low velocity could be offset by a longer length of airway. At many locations the air velocity was too low to give a reasonable pressure drop over the lengths of airway available. During the reconnaissance trips the direct reading anemometer was used to check the speed and uniformity of the air current.

Selected test airways were measured, marked up, and a series of photoprofile pictures taken at suitable intervals. A description of the airway was written and, in some cases, illustrative photographs were also taken of the general appearance.

The tubing was stretched out along the airway between the marked end points, taking care to avoid kinks, and the pitot-static tubes were mounted on tripods and pointed upstream at corresponding positions in the airway cross-section. The micromanometer was connected to the tubing and the barometer and psychrometer were set up nearby.

One team member read the pressure drop at five-minute intervals, while velocity measurements were made independently by the other two members. Generally, each observer made two complete sets of velocity measurements at each of the flow measuring stations. Barometric pressure and wet and dry bulb temperatures were read at the beginning and end of the work at each test section and a mean air density was calculated from the two sets of readings.

3 DISCUSSION AND RESULTS

Even though the average velocity may be determined accurately by taking a large number of readings across the cross-section of the airway, the quantity of air flow depends on the flow area used. The effective area of flow is not necessarily the accurately measured area at the plane where the velocity is measured. The effective flow area seems to be dependent on conditions upstream of the measuring station.

It is well established that the air flow is disturbed for some distance downstream of a bend or an obvious obstruction, and, in this work, velocity measuring stations were carefully selected to ensure that they were well away from the influence of any such disturbances. Nevertheless, at many of the test sites, there was a significant difference in the mean flows measured at the two stations, although consistent measurements were obtained at each individual flow station.

Probably the only way to measure airflow accurately is to build a smooth-lined duct of smaller area than the airway and use a converging inlet to minimize turbulence (McElroy & Richardson 1927). However, such an installation is expensive and impractical for most work of this type.

Mine openings are often extremely variable in shape, size, surface texture and sinuosity. The purpose of the K-factor is to characterize these variables by a single parameter, such that airway resistance can be calculated by the formula:

$$R = KCL/A^3$$

Multiplying the resistance value by the square of the airflow rate will then give the pressure drop through the airway. The resultant value of pressure drop through a given circuit then defines the fan duty required to move the specified quantity of air.

The airway length, L, can generally be determined quite accurately, but C and A, the perimeter and area, are more difficult to define. Besides contributing to R, A is also significant in the definition of flow rate, Q, since Q = Area x Velocity, and velocity is normally what is measured. Area appears in the resistance equation to the third power, so any error in the value used for A will have an exaggerated effect on the resistance. Since it is evident that, in airways of irregular shape, the airstream does not occupy the total area, accurate determination of effective area is not possible by direct measurement. The photoprofile method, for instance, although giving an accurate measurement of actual area at a particular plane, gives an area larger than that which is effectively available in an irregular airway.

It was hoped that the photoprofile pictures, when digitized and super-imposed, could be used as a measure of surface roughness. Although they give an idea of the variability of the airways, they do not really provide a measure of quantifying the roughness. Further, the K-factor of airways varies widely, depending on the roughness of walls; the roughness in turn depends on the properties of the rock, on the location of shotholes, on the obstructions in the airways, etc. Therefore, it is difficult to estimate the value of roughness in very irregular airways. However, once the K-factor is measured, the roughness value can be estimated from equation (6). This value of e can now be used to calculate the K-factor for similar airways with different cross sections. The K-factor table (McElroy & Richardson 1927) was produced mostly for smaller airways with an average A/C value of 0.5 m. The values of A/C for the airways under this study varied from 0.6 m to 1.4 m. The increase in A/C will increase the K-factor, if other conditions remain the same. Table 1 shows the correction factors for K-values for A/C values of 0.75 m and 1.0 m compared to A/C value of 0.50 m at various roughness of the airways. For example, the K-factor for an airway with A/C = 1.0 m will be 0.74 times the K-factor of similar airway with A/C = 0.5 m at the roughness value of 0.1 m.

Table 1. Correction factor for K-values of different cross sections at various roughness values.

Roughness, e m	$\frac{K_{0.75}}{K_{0.50}}$	$\frac{K_{1.0}}{K_{0.50}}$
0.01	0.89	0.82
0.02	0.88	0.80
0.50	0.85	0.77
0.10	0.84	0.74
0.15	0.82	0.72
0.20	0.81	0.70
0.30	0.79	0.68

The K-factors measured are given in Table 2. The K-factors are given in dimensionless form and in old units (10^{-10} lb $\mathrm{min}^2/\mathrm{ft}^4$) along with the values of area/perimeter and surface of roughness. The value of roughness is a useful parameter to calculate the K-factor for similar airways with different dimensions. This can be done using equations (4) and (5).

4 CONCLUSIONS

Systematic evaluation of mine airway friction factor parameters has been performed across a broad array of mining environments. Measurements were carried out using standard methods and equipment in reasonably straight and unobstructed airways.

The photoprofile technique for characterizing airway cross-section is simple and fast in execution but tedious in the data processing stage. Superimposing the pictures gives a good idea of the variability of an airway but does not characterize the surface roughness unless the pictures are taken closely together.

The roughness values for irregular airways can be adequately determined from the field experiment. This is a valuable parameter in predicting the K-factor of airways with different cross sections.

The range of data presented in this study is not intended to be suitable for application by all mining operations. Due to limitations of time, and the number of sites available, the data gathered offer only general applicability to many mining operations. The methodology used, however, may be readily adopted by individual operators and used to perform site specific measurements. The experiment was carefully planned, but the friction factors are best estimates only.

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Table 2. K-Factor and roughness values for straight airways.

Rock/surface type Airway description	A/C m	K-Factor Dimensionless (10^{-10} lb min^2/ft^4)	Roughness Value, e m
Gunited Rectangular, slight obstruction	0.68	0.00491 (32)	0.03
Gunited Rectangular, slight obstruction	0.64	0.00596 (39)	0.05
Gunited Rectangular, slight obstruction	0.64	0.00597 (39)	0.05
Footwall gneiss Rectangular, ramp, clean	1.36	0.00969 (63)	0.32
Gunited Rectangular, blocky	0.76	0.00903 (59)	0.15
Quartz pebble conglomerate Rectangular, clean	1.0	0.00531 (34)	0.06
Quartz pebble conglomerate Rectangular, slight obstruction	0.98	0.00767 (50)	0.14
Sediments & conglomerate Rectangular, obstruction, slightly curved	0.67	0.00888 (58)	0.13
Basaltic andesite Rectangular, slight obstruction	1.08	0.00710 (46)	0.13
Dacite, mafic flow Rectangular, medium obstruction	0.88	0.00717 (46)	0.11
Andesite, dacite Rectangular, medium obstruction	0.82	0.01008 (65)	0.21
Flow breccia Rectangular, medium obstruction	0.86	0.00925 (60)	0.19
Steel arches with corrugated sheeting, slight obstruction, uneven floor	0.91	0.01017 (66)	0.24