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AN ANALYSIS OF AIR VOLUME-FLOWRATE DETERMINATIONS FOR MINES

Jeffery L. Kohler

Pennsylvania State University, University Park, PA 16802 (U.S.A.)

and Edward D. Thimons

Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA 15213 (U.S.A.)

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ABSTRACT

The proper control and distribution of ventilation air is a key aspect in the productivity of an underground mining operation, and is crucial to the health and safety of mine workers. Accurate measurement of air velocity is an essential component in achieving effective ventilation planning and control. However, the measurement methodology and application is problematic, especially in the use of correction factors. This paper examines the accuracy of these factors as they are affected by measurement location, instrument, and flow characteristics. Definitive recommendations are presented to improve the accuracy of flowrate determinations.

BACKGROUND

Air velocity measurements are taken in mines to satisfy statutory requirements and to support mine planning activities. In a coal mine, for instance, these measurements are taken throughout the mine at intervals that range from minutes to weeks based on 30 CFR (Code of Federal Regulations) requirements. Sometimes the measurements are taken to determine only the air velocity, but in most cases it is the average volume flowrate that is of interest.

Calculation of this parameter may involve the use of as many as three correction factors. The first is an instrument correction factor, which is related to a calibration curve supplied by the manufacturer of the instrument. Although this factor is not of concern in this study, it is essential to calibrate measurement devices periodically and to apply the instrument correction factor. The second correction factor is a location factor which is used to account for erroneously low or high readings that are obtained at certain undesirable locations, such as near obstructions and intersections. As will be discussed later, this factor should not be used. Rather, appropriate sites

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should be chosen according to the guidelines presented in this paper.

The third correction factor, and the one of interest here, is commonly known only as "correction factor." The measured velocity represents the velocity at one point, or sometimes several points, and is not the *average* velocity required to compute *average* volume–flowrate. The purpose of this correction factor is to convert the measured value to the true average value. Determination of this correction factor was the major thrust of this study.

This U.S. Bureau of Mines funded study consisted of three components: an exhaustive literature review and analysis; an extensive in-mine data collection effort; data analysis and formulation of recommendations. A complete record of the work can be found in ref. [1] and a concise summary of the project is presented in ref. [2]. While the emphasis of this paper is on the determination of correction factors, based on the in-mine experiments, there are some interesting findings from the literature review worth noting here.

The literature contains many recommendations and guidelines for correction factors and measurement methodology. Recommended correction factors for a specific instrument and method, for instance a vane anemometer centerpoint measurement, range from 0.6 to 1.2. Correction factors to account for adverse measurement locations are also as diverse. Analysis of the literature suggests one reason for diversity. In some cases erroneous experimental procedures were to blame, but in many other studies the experiment methodology was satisfactory, thereby suggesting a more fundamental problem. The experimental work done in this study was designed to eliminate weaknesses in past work, and to finally define an accurate set of correction factors. One result of this study is an explanation of the diversity found in the technical literature.

EXPERIMENTAL METHODOLOGY AND APPARATUS

Three mines, two metal–nonmetal and one coal, were selected for detailed in-mine experimentation. Limited experimentation was performed in two other mines to define appropriate sample sizes for the major work at the three selected mines.

Two important considerations in the experiment design were the establishment of adequate controls so that true volume flowrate could be computed, thereby allowing comparisons based on accuracy rather than precision: the selection of sufficient sample sizes to facilitate statistical validation and analysis of the results. Both of these considerations were satisfied. The latter was achieved utilizing standard procedures for statistical experiment design [3] by which sample size can be determined for a specific bound on the error of estimation, based on an estimate of the population standard deviation. The establishment of adequate controls was achieved by design, and is summarized here.

A control station was established in each mine so that the true volume flowrate could be determined. This consisted of an airtight stopping with a pitot-tube array constructed across the aircourse where the experimentation occurred, as shown in Fig. 1.

The total and static pressure heads in the

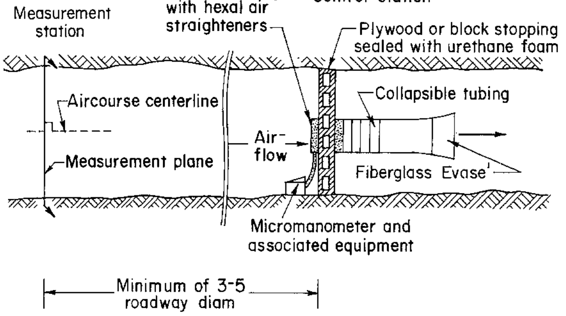


Fig. 1. Diagram of the control station arrangement for in-mine experiments.

array were measured using a manometer connected to the array in the standard manner, which allowed direct reading of the velocity head. A commercially available manometer was selected for its mine-worthiness and accuracy to within 1.0%. An engineer's barometer and a sling psychrometer were used to collect data necessary for computation of the air density. The former was accurate to within 5% and the latter to within 1.0%. The photographic method was used to determine the cross-sectional area at the measurement station.

The control station was always located five roadway diameters downstream of the measurement station to eliminate the effects of the control stopping on the measurement station. During a preliminary trip to each mine, the candidate sites were monitored over a full shift to detect any changes in flow that occurred as a result of mining activity. Smoke tubes were also utilized to detect any leakage or abnormal flow patterns that could introduce error into the experiments.

The air velocity measurement methods included in this study are shown in Table 1.

TABLE 1

Measurement methods included in this study

	Identification *
VANE ANEMOMETER **	
Centerline	
Handheld	1
Stickheld	2
Remote operator	3
Continuous traverse	
Handheld	4
Stickheld	5
Split traverse	
Handheld	6
Stickheld	7
Timed-point traverse ***	
Handheld	10
Stickheld	11
VORTEX SHEDDING ANEMOMETER †	
Centerline: Handheld	21
Split traverse: Handheld	22
Continuous traverse: 2 min	27
Timed-point traverse: Handheld	28
SMOKE TUBE	
Centerline:	
Leading edge, 10 ft	41
Leading edge, 20 ft	42
Leading edge, 30 ft	43
Cloud center, 20 ft	44
OIL OF WINTERGREEN ††	
50 ft	50
100 ft	51

* These identification numbers are used later in the paper.

** Ball-bearing low speed vane anemometer, calibrated at the National Bureau of Standards.

*** This is similar to a continuous traverse except that the anemometer remains fixed at each grid position for a period of time, typically 10 seconds, and is then moved to the next grid position.

† Also known as an air-draft sensor, calibrated by the manufacturer.

†† In this method two people are stationed a known distance apart. The oil of wintergreen (methyl salicylate) is released by the one person, while the other records the time elapsed until the oil of wintergreen "clouds" were detected, by smell.

RECOMMENDATIONS FOR MEASUREMENT OF AIR VELOCITY

The practical measurement of air velocity is based on the need to define airflows in the mine; accordingly, the needs of the ventilation engineer will normally dictate general locations for and the frequency of measurements. The person making the measurement is often faced with one or more of the following issues:

- What influence will the measurement observer (operator) have on the final reading?
- The measurement must be taken at an adverse location, such as a bend or intersection; what factor can be used to correct the reading?
- Would a different instrument or measurement method improve the accuracy of the reading?

- What correction factor should be applied to determine the average volume flowrate?

These issues were addressed by this study, and the answers to these questions are presented here.

Operator influence

The person taking the measurement (operator) can dramatically affect the quality of the measurement depending upon the operator's proximity to the instrument, as well as the operator's technique. In general, it is assumed that stickheld or remote placement of the measurement device will yield better results than when the device is handheld.

However, the improved accuracy expected from the stickheld measurement may not be realized in certain cases. If the anemometer is not held perpendicular to the airflow the accuracy will be degraded. Some observers have more difficulty in keeping it perpendicular when the anemometer is stickheld, and particularly when using traversing methods. At low air speeds the error due to this yaw angle will be more noticeable.

It was found that handheld and stickheld measurements had a similar level of accuracy; thus in many cases the stickheld measurement was not superior. In fact, at low velocity (approx. 60 fpm) the handheld measurements were better than the stickheld measurement. The presence of the operator's body in the measurement plane alters the airflow and thereby affects the measurement. However the net benefit of using a stickheld device over a handheld one may not be as significant as is often assumed. The best results were achieved in this study by holding the device straight out to the side of the observer's body and just slightly upstream.

All things being equal, the readings obtained by two different operators are likely to be slightly different. To investigate this, two different observers made a series of measurements at the same site. The resulting data differed by 1 to 2%, even though both observers used the same equipment and proper techniques.

Certain conditions can increase the importance of the operator's influence. At lower velocities, proximity effects are accentuated and the operator's technique (and body shape) become more important. If the device has to be moved during the measurement, as in a traverse, precautions must be exercised to keep it perpendicular to the airflow. The proximity of the observer to the device should remain constant, although this is problematic in practice.

In general, if good technique is practiced, the resulting error will be negligible when compared with other error sources.

Location selection

The location of an air velocity measurement within the mine is usually determined by a statutory or engineering requirement. Often, these locations are less than ideal in that the airflow is partially obstructed by a roof fall, equipment, or timber sets, or is altered by a nearby bend, intersection, and so forth. It would be convenient in these cases to have a correction factor that would correct for the error introduced by the obstruction. This correction factor would be used in addition to the correction factor that transforms the measured velocity to average velocity. It would also be desirable to establish criteria for site selection under these less than ideal conditions. For example, a helpful criterion would specify the minimum downstream distance at which a measurement can be made from an obstruction, which is blocking a certain percentage of the airflow, and yield a result which had an acceptable level of error.

As indicated earlier, the use of factors to correct readings taken at adverse locations has been heavily investigated; but there is so much disagreement among investigators that it is difficult to use the reported factors. Experiences during this study have led to the conclusion that such factors are useless for general application. They tend to be valid for only one specific situation in a given mine, and only at one specific velocity. Any attempt to generalize them is futile. The reason for this lies in the behavior of isovels (flow patterns) and the influence of these isovels on the measurement. This phenomenon is explored later in this paper.

Given that generalized factors cannot be employed to correct readings taken at adverse locations, the initial site selection becomes even more important. Based on the results of this investigation and the literature review, the following site selection guidelines are presented:

- Measurements made at locations near obstructions or changes in the aircourse will adversely affect measurement accuracy and should be avoided when at all possible.
- The downstream effect of obstructions or changes are much more pronounced than upstream effects. Consequently, measurements should be obtained on the upstream side of the obstruction or change.
- In the event that measurements must be made between two different obstructions or changes, and it is impossible to get the recommended distances upstream or downstream of either, optimum results will be obtained by selecting a measurement point between the two which is one-third the distance upstream of the second obstruction and two-thirds of the distance downstream from the first construction as encountered in the normal direction of airflow.
- Measurements should always be made at a minimum distance of 3 roadway diameters upstream of an obstruction and 10 roadway diameters downstream of an obstruction. If any doubt exists, these distances should be increased.
- Smoke tubes are a useful tool for detecting unusual air patterns. Measurements should not be made in locations where the smoke reveals large vortices; maximum flow near the roof, ribs, or floor is encountered; or splitting of the air occurs within the aircourse.
- At less than ideal locations, measurement accuracy can be substantially improved by performing a timed-point traverse rather than a single-point measurement.
- The construction of an artificial measurement station may be justified in locations where measurements are made frequently, but where the airway characteristics, such as the presence of timber sets may be a constant source of error.

It is recognized that sometimes there is little choice as to the measurement site. It must also be recognized that generalized location correction factors to improve accuracy are not feasible for adverse measurement locations; rather, error can only be minimized by following the aforementioned guidelines as closely as possible.

Measurement methods and devices

The measurement methods listed in Table 1 have attendant advantages and disadvantages in their application. Although the choice of a particular method is often based on operator preference, the relative accuracy of the methods should also be considered. Given good technique and calibrated devices, the accuracy achieved with a certain method will be affected by the velocity of the flow, the characteristics of the isovel at the measurement plane and the operator. The effect of operator influence and site selection on measurement accuracy, for certain methods, was addressed in the previous sections.

The physical characteristics of the measurement device affect the device's accuracy in airstreams of different velocity. Thus, the free stream velocity in which the ball-bearing vane anemometer is useful is limited by the friction of the ball-bearing drive mechanism.

Similarly, certain sampling methods are limited by the free stream velocity. The continuous traverse utilizing a mechanical response device, such as the ball-bearing vane anemometer, will be subject to larger errors at lower velocities if the traverse speed of the device is not reduced proportionately. The accuracies found for the devices and methods included in this study are shown in Table 2.

Analysis of the data obtained reveals some interesting results.

- The ball-bearing vane anemometer yields the most accurate results through the widest range of conditions.
- For specific velocity ranges, certain devices can be selected over others to yield increased accuracy of the measurement. For example, the vortex shedding anemometer and the vane anemometer should not be used in flows where the free stream velocity is less than 62 fpm; the smoke tube, however, yields measurements of acceptable accuracy in this range.
- The oil of wintergreen method did not provide satisfactory results in flows less than 135 fpm because of its operational characteristic, i.e., the oil of wintergreen droplets precipitated out of the airstream causing increased errors. It did, however, yield accurate measurements in the velocity range of 135 to 340 fpm.
- At velocities greater than 135 fpm, all de-

TABLE 2

Comparative accuracy of different air velocity determination methods, percent

Average velocity (fpm)	35	53	62	93	135	187	340	650
VANE ANEMOMETER								
Centerline								
Handheld	±5	±4	±1	±2	±2	±1	±2	±1
Stickheld	±7	±3	±1	±2	±2	±1	±1	±1
Remote operator	NAp *	±3	±2	±2	±1	±1	±1	±2
Continuous traverse								
Handheld	±2	±1	±1	±2	±1	±1	±1	±2
Stickheld	NAp	±3	±1	±1	±1	±1	±1	±1
Split traverse								
Handheld	±5	±2	±1	±1	±1	±1	±1	±2
Stickheld	NAp	±3	±1	±2	±1	±1	±1	±1
Time-point traverse								
Handheld	±3	±2	±1	±2	±1	±1	±1	±1
Stickheld	±17	±10	±12	±2	±2	±2	±1	±2
VORTEX SHEDDING ANEMOMETER								
Centerline: Handheld	NAp	±3	±6	±2	±1	±1	±3	±1
Continuous traverse: 2 min	NAp	±3	±2	±2	±1	±1	NAp	±1
SMOKE TUBE								
Centerline								
Leading edge, 10 ft	±9	±7	±3	±5	±4	±5	±7	NAp
Leading edge, 20 ft	±4	±7	±2	±4	±4	±3	±7	NAp
Leading edge, 30 ft	±6	±5	±2	±3	±3	±2	±3	NAp
Cloud center, 20 ft	±9	±7	±4	±5	±6	±4	±4	NAp
OIL OF WINTERGREEN								
50 ft	NAp	±6	±4	NAp	±5	NAp	NAp	±3
100 ft	NAp	NAp	NAp	NAp	±3	±4	±2	NAp

* NAp: Not applicable or no readings taken.

vices performed at an acceptable level of accuracy.

The characteristics of the isovel at the measurement site affects the accuracy of the computed flowrate, rather than the measured velocity. As the isovel becomes more robust and less well behaved, an increased number of samples or measurement points within the measurement plane will be required to improve the accuracy of the volume flowrate predicted by multiplying the velocity measurement with the cross-sectional area. In this case, selection of a traverse-type of method will tend to reduce the error of the prediction. This is discussed in more detail in the next section.

Correction factors

The volume flowrate of air in an aircourse is the product of the average measured velocity and the cross-sectional area of the aircourse where the velocity was measured. If this cross-sectional area or measurement plane is representative of the aircourse and is not located near any obstructions or changes in the aircourse, then an accurate volume flowrate can be obtained, if the measured and average velocities are equal. However, most devices do not measure the average velocity. Rather, one or more points in the measurement plane are sampled, i.e. a velocity measurement is made, and then this point(s) is mathematically manipulated to obtain a number that is called the average velocity.

The justification for this mathematical transformation is an a priori knowledge of the isovel or flow pattern. In this sense, the velocity measurement method (centerline, single point, multipoint traverse with a linear grid, multipoint traverse with a log grid, etc.) can be viewed as a sampling scheme. It is well

TABLE 3

Summary of correction factors (cf's) for mine 1, true velocity at 62, 187, and 340 fpm

Method	62 fpm			187 fpm			340 fpm		
	cf	Accuracy * (%)	Range	cf	Accuracy (%)	Range	cf	Accuracy (%)	Range
1	0.76	±6	0.71–0.81	0.72	±6	0.68–0.76	0.68	±6	0.64–0.72
2	0.73	±6	0.69–0.78	0.78	±6	0.74–0.83	0.76	±7	0.71–0.81
3	0.78	±6	0.73–0.83	0.83	±6	0.78–0.87	0.79	±5	0.75–0.84
4	0.78	±7	0.73–0.84	0.83	±6	0.79–0.88	0.78	±6	0.74–0.83
5	0.81	±6	0.76–0.86	0.94	±6	0.88–0.99	0.89	±6	0.84–0.94
6	0.74	±6	0.70–0.79	0.82	±6	0.77–0.87	0.77	±6	0.73–0.82
7	0.84	±6	0.79–0.89	0.95	±6	0.89–1.01	0.88	±6	0.82–0.93
10	0.79	±6	0.74–0.84	0.88	±6	0.82–0.93	0.84	±6	0.78–0.89
11	0.87	±6	0.81–0.93	0.95	±6	0.90–1.01	0.90	±6	0.84–0.95
21	0.88	±17	0.73–1.03	0.91	±7	0.85–0.97	0.61	±6	0.58–0.65
22	NAp	NAp	NAp	NAp	NAp	NAp	0.77	±6	0.72–0.82
27	0.64	±11	0.57–0.71	0.82	±6	0.77–0.87	0.73	±8	0.67–0.79
28	0.85	±7	0.79–0.91	0.91	±6	0.86–0.97	NAp	NAp	NAp
41	0.60	±8	0.56–0.65	0.67	±10	0.60–0.73	0.69	±12	0.61–0.77
42	0.63	±7	0.59–0.68	0.72	±8	0.66–0.77	0.72	±8	0.66–0.78
43	0.65	±7	0.60–0.69	0.71	±8	0.66–0.75	0.72	±8	0.66–0.78
44	0.70	±8	0.65–0.76	0.80	±9	0.73–0.86	0.74	±9	0.68–0.81
50	0.78	±9	0.71–0.84	NAp	NAp	NAp	NAp	NAp	NAp
51	NAp	NAp	NAp	0.90	±9	0.83–0.98	0.91	±7	0.84–0.97

* 99% confidence level.

known from mathematical sampling theory that a few samples can be used to approximate the behavior or characteristics of the population of all values in the sample space, provided that sampling is performed in accord with theorems or practices that utilize a priori knowledge of the population. In this case, the population is simply the set of all point velocities that define the airstreams.

The published correction factors, as noted earlier, span a large range and are often so contradictory that it is difficult to apply them. In fact, the major motivation for this study was to resolve the correction factor issue. Some previous studies suffered from a lack of proper controls in their experiments, or poor experimental procedure. However many past researchers conducted properly designed and controlled experiments, and still ended up with divergent results. The correction factors developed during the course of this study are presented in Tables 3, 4 and 5. Even a casual glance at these tables reveals that these correction factors also span a large range and in certain cases appear contrary to expectation. Thus it is clear that it is difficult to know a priori, the flow pattern.

The problems here were attributed to the site-specific nature of the measurement plane, just as some previous researchers had done with their results. However an important task during this study was to establish a relationship between correction factors and the site-specific variables such as air velocity, aircourse height-to-width ratio, rubbing surface characteristics, cross-sectional area, and measurement device characteristics, among others. The goal was to develop quantitative relationships among the variables so that correction factors could be "corrected" for site specific characteristics.

The raw data sets were systematically analyzed. Various statistical estimators such as mean, standard deviation, variance, and correlation coefficients were computed. Standard tests on the means and the variances were performed [4]. Statistically significant hypotheses about the relationships among the variables could not be developed. The Principle Components method of factor analysis was performed without success, even though this is often useful when other methods are unable to quantify variable relationships [5].

Curve fitting procedures are appropriate whenever there is good reason to suggest a physical basis for relationships among the variables. This is certainly the case for this problem. However, these procedures have an innate pitfall: it is always possible to fit a curve to a set of data, even in the absence of any meaningful relations among the variables. Of course, this is easily checked by applying the resulting equation to new data, and comparing the predicted value to the actual value. For the purposes of this project the general

TABLE 4

Summary of correction factors (cf's) for mine 2, true velocity at 35 fpm

Method	cf	Accuracy * (%)	Range	Method	cf	Accuracy * (%)	Range
1	0.74	±12	0.65–0.83	31	0.74	±19	0.60–0.88
2	0.70	±10	0.63–0.77	32	0.92	±17	0.76–1.07
3	0.81	±12	0.71–0.91	41	0.50	±14	0.43–0.57
5	0.56	±7	0.52–0.60	42	0.49	±9	0.45–0.54
7	0.54	±10	0.48–0.59	43	0.46	±11	0.41–0.52
11	0.51	±8	0.47–0.56	44	0.66	±14	0.57–0.75
21	1.77	±22	1.38–2.16				

* 99% confidence level.

TABLE 5

Summary of correction factors (cf's) for mine 3, true velocity at 52, 93, 135, and 650 fpm

Method	52 fpm			93 fpm (Observer No. 1)			93 fpm (Observer no. 2)		
	cf	Accuracy * (%)	Range	cf	Accuracy (%)	Range	cf	Accuracy (%)	Range
1	0.92	±9	0.84–1.00	0.87	±7	0.81–0.93	0.82	±7	0.76–0.88
2	0.89	±9	0.81–0.97	0.92	±7	0.86–0.98	0.93	±7	0.87–1.00
3	0.94	±8	0.87–1.01	0.96	±7	0.90–1.03	NAp	NAp	NAp
4	0.78	±8	0.72–0.85	0.89	±7	0.83–0.95	0.88	±7	0.82–0.93
5	0.91	±6	0.85–0.97	0.90	±7	0.84–0.96	0.94	±7	0.88–1.00
6	0.91	±8	0.84–0.98	0.87	±6	0.81–0.92	0.91	±7	0.85–0.90
7	0.92	±7	0.86–0.99	0.89	±6	0.84–0.95	0.97	±7	0.91–1.03
10	0.70	±8	0.65–0.76	0.86	±7	0.80–0.92	0.83	±7	0.78–0.88
11	0.88	±7	0.81–0.94	0.89	±7	0.83–0.95	0.92	±7	0.85–0.98
21	1.16	±15	0.98–1.33	0.84	±7	0.78–0.90	0.90	±9	0.82–0.99
27	0.48	±8	0.44–0.52	0.84	±7	0.78–0.90	0.80	±7	0.74–0.85
28	1.02	±8	0.94–1.09	1.04	±7	0.96–1.11	1.01	±7	0.94–1.08
41	0.85	±12	0.75–0.95	0.79	±10	0.72–0.87	NAp	NAp	NAp
42	0.84	±12	0.75–0.95	0.82	±9	0.75–0.90	NAp	NAp	NAp
43	0.86	±10	0.77–0.95	0.81	±8	0.75–0.87	NAp	NAp	NAp
44	1.10	±12	0.96–1.23	0.89	±10	0.88–0.97	NAp	NAp	NAp
50	0.80	±11	0.71–0.89	NAp	NAp	NAp	0.85	±10	0.77–0.94
51	NAp	NAp	NAp	NAp	NAp	NAp	0.82	±10	0.73–0.90

Method	135 fpm			650 fpm		
	cf	Accuracy (%)	Range	cf	Accuracy (%)	Range
1	0.85	±6	0.79–0.90	0.90	±6	0.85–0.95
2	0.89	±7	0.83–0.95	1.06	±6	1.00–1.12
3	0.92	±7	0.85–0.98	1.12	±6	1.06–1.19
4	0.89	±6	0.84–0.94	1.07	±7	0.99–1.15
5	0.95	±6	0.90–1.01	1.10	±7	1.03–1.10
6	0.89	±6	0.83–0.94	0.96	±6	0.90–1.01
7	0.97	±6	0.91–1.03	1.13	±7	1.06–1.20
10	0.87	±6	0.82–0.93	0.96	±6	0.90–1.01
11	0.96	±6	0.90–1.02	1.05	±6	0.99–1.12
21	0.84	±7	0.78–0.90	0.84	±7	0.79–0.90
27	0.89	±6	0.84–0.95	0.89	±6	0.84–0.95
28	0.96	±6	0.90–1.02	0.91	±6	0.85–0.96
31	0.92	±10	0.83–1.01	NAp	NAp	NAp
32	1.01	±10	0.91–1.12	NAp	NAp	NAp
41	0.81	±9	0.74–0.89	NAp	NAp	NAp
42	0.87	±9	0.80–0.95	NAp	NAp	NAp
43	0.86	±8	0.79–0.93	NAp	NAp	NAp
44	0.94	±11	0.84–1.04	NAp	NAp	NAp
50	0.97	±10	0.88–1.07	NAp	NAp	NAp
51	0.96	±8	0.89–1.04	1.10	±8	1.02–1.10

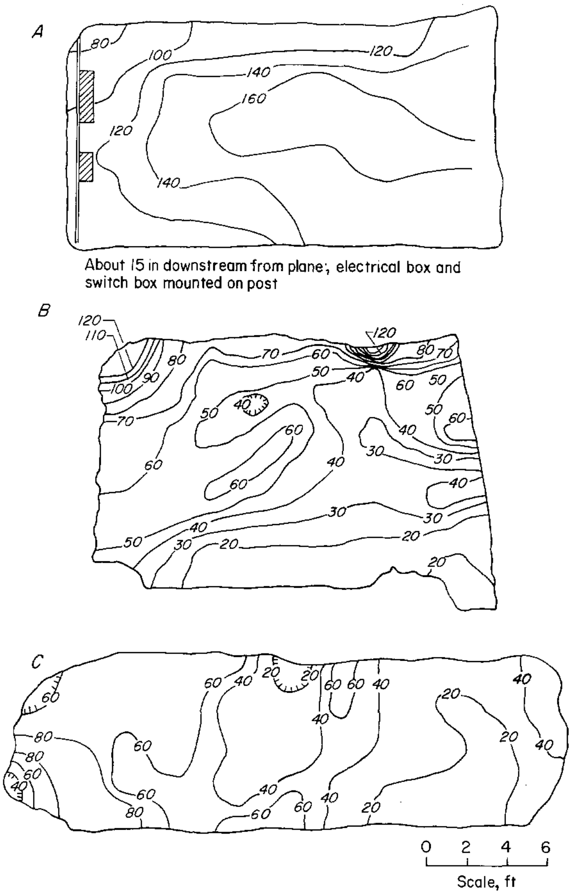
* 99% confidence level.

polynominal model was used. The data set was sufficiently robust that some of the data could be held back during the curve fitting process, and then used to test the "goodness of the fit."

The resulting polynominal equation predicted a correction factor based on the site-specific variables mentioned before. There were large quantities of data from three mines and modest amounts from two others. Typically, data from three of the five mines was used to develop the polynominal equation, and then data from the other two was used to test the equation. Other combinations were used such as taking data from a few sites in all mines to develop the equation, and then using the remaining data to test the equation.

The predicted correction factors were, in all cases, no better than the existing tables of factors. The inability to quantify the relationship between the variables and the correction factor was attributed to two problems. First it is difficult to quantify the value of certain variables, e.g. rubbing surface characteristics for instance. This will contribute to the inaccuracy of the prediction. Second, it is apparent that not all of the relevant variables are being accounted for in the model. This will have a significant impact on the quality of the prediction as well. A graphical analysis is useful to put the problem in perspective.

Data for the construction of isovels were collected at each measurement plane and then plotted. The resulting isovels, some of which are shown in Fig. 2, are enlightening. It was determined that the mathematical application of different sampling schemes to a particular isovel would result in very different results. It was also found that isovels for different velocity ranges changed unpredictably, as shown in Fig. 3. This further illustrates the problem of applying a correction factor. Despite any shortcomings in the application of generalized correction factors, the industry needs such factors for routine ventilation work. Therefore, an attempt has been made to develop a generalized correction-factor table, although as indicated previously, the results are questionable because of the site-specific characteristic of correction factors.



About 15 in downstream from plane; electrical box and switch box mounted on post

Fig. 2. Isovels of measurement plane: A, mine 1, $V = 180$ fpm; B, mine 2 $V = 35$ fpm; C, mine 3, $V = 52$ fpm.

A set of correction factors directly relating to the experiments conducted is given in Table 6. These correction factors represent the values recorded at different mines and at the indicated air velocities. The appropriate correction factor for any given pair (measured velocity, measurement method) can be obtained by interpolating between velocity ranges for the method selected.

An alternative approach would be to use a predictive equation which incorporates those variables which affect the correction factor.

TABLE 6

Summary correction factors, by velocity, for different measurement methods

Method	Air velocity (fpm)								Mean value over † all velocities
	35 **	52 ***	62 *	93 ***	135 ***	187 *	340 *	650 ***	
1	0.74	0.92	0.76	0.87	0.85	0.72	0.68	0.90	0.81 (0.80)
2	0.70	0.89	0.73	0.92	0.89	0.78	0.76	1.06	0.85 (0.88)
3	0.81	0.94	0.78	0.96	0.92	0.83	0.79	1.12	0.89 (0.92)
4	NAp	0.78	0.78	0.89	0.89	0.83	0.78	1.07	0.86 (0.89)
5	0.56	0.91	0.81	0.90	0.95	0.94	0.89	1.10	0.89 (0.96)
6	NAp	0.91	0.74	0.87	0.89	0.82	0.77	0.96	0.86 (0.86)
7	0.54	0.92	0.84	0.89	0.97	0.95	0.88	1.13	0.90 (0.96)
10	NAp	0.70	0.79	0.86	0.87	0.88	0.84	0.96	0.84 (0.88)
11	0.51	0.88	0.87	0.89	0.96	0.95	0.90	1.05	0.88 (0.95)
21	1.77	1.16	0.88	0.84	0.84	0.91	0.61	0.84	0.96
27	NAp	0.48	0.64	0.84	0.89	0.82	0.73	0.89	0.76
28	NAp	1.02	0.85	1.04	0.96	0.91	NAp	0.91	0.96
41	0.50	0.85	0.60	0.79	0.81	0.67	0.69	NAp	0.70
42	0.49	0.84	0.63	0.82	0.87	0.72	0.72	NAp	0.73
43	0.46	0.86	0.65	0.81	0.86	0.71	0.72	NAp	0.72
44	0.66	1.10	0.70	0.89	0.94	0.80	0.74	NAp	0.83
50	NAp	0.80	0.78	NAp	0.97	NAp	NAp	NAp	0.85
51	NAp	NAp	NAp	NAp	0.96	0.90	0.91	1.10	0.94

* mine 1

** mine 2

*** mine 3

† The numbers in parentheses are average values for the vane anemometer for all velocities greater than 62 fpm.

TABLE 7

Coefficient for generalized correction factors, by method, using the quadratic equation

Method	Points in analysis	Coefficient of eqn. 1			Mean error (%)
		a	*b*	*c*	
1	9	0.833	-9.96×10^{-4}	1.55×10^{-6}	8.4
2	9	0.855	-4.39×10^{-4}	1.12×10^{-6}	10.7
3	8	0.915	-7.23×10^{-4}	1.57×10^{-6}	8.3
4	8	0.869	-4.92×10^{-4}	1.20×10^{-6}	6.5
5	9	0.764	$+9.53\times10^{-4}$	-7.27×10^{-7}	12.3
6	8	0.910	-7.13×10^{-4}	1.198×10^{-6}	7.1
7	9	0.777	$+8.87\times10^{-4}$	-5.92×10^{-7}	13.7
10	8	0.764	$+5.24\times10^{-4}$	-3.68×10^{-7}	5.9
11	9	0.737	-1.25×10^{-3}	-1.25×10^{-6}	13.5
21	9	1.420	-4.62×10^{-3}	$+5.79\times10^{-6}$	24.0
27	8	0.634	$+1.03\times10^{-3}$	-1.04×10^{-6}	6.9
41	7	0.576	$+2.01\times10^{-3}$	-5.07×10^{-6}	16.4
42	7	0.539	$+2.95\times10^{-3}$	-7.27×10^{-6}	15.4
43	7	0.542	$+2.85\times10^{-3}$	-7.02×10^{-6}	16.9
44	7	0.762	-1.53×10^{-3}	-4.08×10^{-6}	17.4
50	4	0.822	-1.72×10^{-3}	$+2.09\times10^{-5}$	1.4
51	5	0.877	-1.43×10^{-5}	$+5.39\times10^{-7}$	5.3

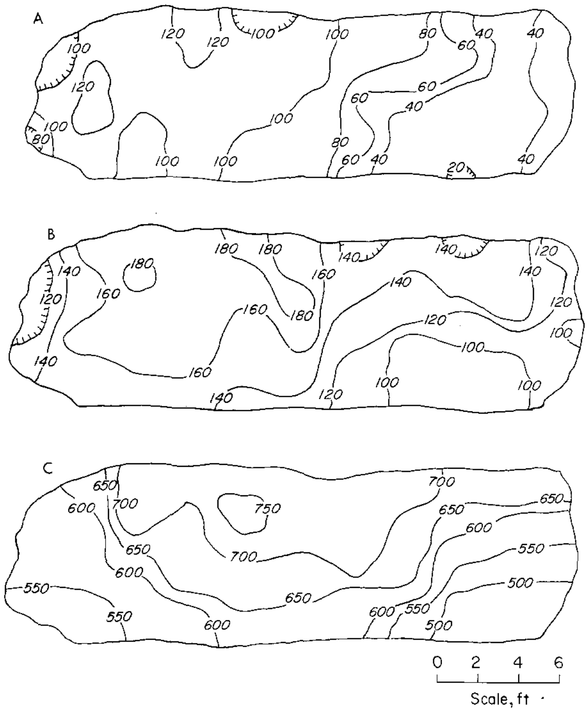


Fig. 3. Mine 3 isovels at measurement plane: A, $V = 93$ fpm; B, $V = 135$ fpm; C, $V = 650$ fpm.

The poor experience with the general polynomial model, coupled with the difficulty in defining values for the identified variables, eliminates it from consideration. Another possibility is to use a regression equation to relate the change in air velocity to the correction factor. Since correction factors are known to change with velocity, this is at least a plausible approach. It was found that a quadratic equation was satisfactory and is given by,

$$cf = a + bV + cV^2, \tag{1}$$

where
cf = correction factor,
V = measured air velocity, and
a, b, c = coefficients.

Table 7 lists coefficients a, b, and c. The last column in Table 7 is an indication of the range of expected error associated with the measurement technique and use of the quadratic equation for estimating the correction factor. This is the ratio of the standard deviation of the measured mean correction factor (last column in Table 6) for each measurement method.

The large error range shown in Table 7 is, again, a reflection of the site-specific nature of correction factors, and the consequent difficulty in generalizing. Since this table is based on a curve fitting to the collected data, its general applicability is subject to debate.

CONCLUSIONS

This investigation has addressed the development and use of correction factors for air velocity measurements and the establishment of location guidelines for making measurements. Long-standing problems in this area, contributed in large part by the disagreements within the technical literature, have been resolved.

Guidelines for selecting suitable locations for making air velocity measurements have been defined and must be strictly applied. Otherwise results will be erroneous. The use of factors to correct for adverse locations is not technically justified. In fact, a strong case has been made against the use of such factors.

Correction factors are useful to convert instrument readings to average values; a set of correction factors has been developed and is presented in this report. As in previous investigations, the correction factors developed here appear to diverge and are not always consistent with intuitive expectations. In contrast with the approaches taken in previous investigations, this fact was recognized and analyzed. It was found that computed correction factors are extremely site-specific, and specific to a velocity range. Accordingly, it is difficult to generalize tables of correction factors. It was also impossible to establish a general mathematical relationship that would be useful to predict a correction factor given mine-specific information. The diversity found in published correction factor tables, as well as the ones developed during this study, was explained by examining the isovels at the measurement sites. The effect of site specific conditions on the isovel, and the resulting effect on the correction factor, for a given measurement method, accounts for the wide range of correction factors.

It was found that accurate measurements could be obtained with most of the methods studied. Multiple-point rather than single-point measurements will give slightly better accuracy over the widest range of site conditions. While operator influence on the measurement is widely appreciated, the results of this study suggest that if good technique is used, then operator influence is minimal, and the difference between a stickheld and hand-held measurement is not as significant as expected. Of course, as the flow velocity decreases, operator influence can become more pronounced.

The accuracy of the correction factors of Table 7 should be adequate for most mine work, especially considering that the stated errors are worst case expectations; significantly better accuracy would be predicted for many cases. The level of accuracy required for routine work is itself debatable. When questioned, practicing ventilation engineers most often stated a need to be within 10 to 20 percent of the true value. This is compatible with the expected error associated with the use of a correction factor.

The use of the correction factor is necessary and is technically justified in mine ventilation measurements, as long as the underlying basis and limitations of these factors are recognized.

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