# Sonic anemometer airflow monitoring technique for use in underground mines

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ABSTRACT: Satisfying statutory requirements of total air quantity and air velocity in an underground mine requires airflow measurements. In this paper instrumentation and sampling strategies for accurate monitoring of airflow in an entry using two-axis and three-axis ultrasonic anemometers are evaluated. Currently other types of anemometers, mainly vane anemometers, are used for measurements underground. The drawbacks of these devices include following strict operational procedures and an inability to measure low flows. Ultrasonic anemometers are known for their accuracy, capability to measure low flows, and continuous measurement characteristics that have made them popular in various fields of research. Several steps are required to enable the use of ultrasonic anemometers underground. Results and lessons learned from experiments at the NIOSH Ventilation Gallery and its Experimental Mine are presented. Calibration of instruments and data acquisition is explained. Three instruments were used simultaneously in the underground testing facility for anemometer comparison and sampling location analysis. Continuous single-point measurements with ultrasonic anemometers and vane anemometer traverse measurement results underground were compared. The comparison showed slightly lower air velocity values with the ultrasonic anemometers. Factors affecting the selection of sampling locations underground were investigated to determine optimal locations. The optimal measurement location in a straight tunnel was found approximately ¼ diameter from the tunnel walls. For uneven flows, curves, and obstructed tunnels several point measurements across the entry cross-section or flow simulations are recommended. Two ultrasonic anemometers were assessed in the laboratory, for the influence of dust deposition. The effects of two different dusts, rock dust and coal dust were evaluated. The dust exposure testing showed that coal dust rarely affected the ultrasonic anemometers and was easy to clean off of the instruments. Rock dust, however, tended to stick and cake on the instruments. Cleaning was required to avoid loss of signal with heavy build-up of dust.

## 1 Introduction

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 methods of determining the air volume flow rates are necessary to properly control and distribute the air (Thimons & Kohler, 1985).

The airflow in a tunnel is calculated from measured air velocity and cross-sectional area values. In underground mines cross-sectional areas are usually measured with a tape measure. A laser device can be used in locations where intrinsically safe instruments are not required. Air velocity is typically measured by a rotating vane anemometer traverse or by using point measurements. The vane anemometer has been the primary instrument for air velocity measurement in mines since the early 1900s (De La Cruz, 1982). Other devices, like hot wire anemometers and pitot tubes can also be used for measuring air velocity. Lately, more sophisticated devices like vortex shedding anemometers and ultrasonic anemometers have appeared in other fields of research and they have already been used extensively in meteorology.

In this paper the feasibility of using ultrasonic anemometers underground is evaluated. The measurement results of ultrasonic anemometers and rotating vane anemometers are compared. The influence of dust deposition was tested in the laboratory to evaluate maintenance requirements of these devices when installed underground. Also, choosing a measurement location with a representative air velocity is studied. The objective of the research is to give guidance for successful and accurate use of ultrasonic anemometers in an underground setting.

A mine operator can use an ultrasonic instrument to help them comply with ventilation requirements such as air velocity in the belt entry, and total air quantity in the belt entry and primary escapeway. However, ultimate compliance is determined by MSHA by making traverse velocity measurements in the entries using a vane anemometer. Currently, ultrasonic anemometers do not have an MSHA certification for intrinsic safety.

## 2 Measuring air velocity

### 2.1 Rotating vane anemometer

In operating mines the most common instrument for air velocity measurements is a rotating vane anemometer. Either point measurements or anemometer traverses are used to check for air velocity in an entry. The advantages of rotating vane anemometers include small size, portability, intrinsically safe for use throughout the mine, minimal maintenance, and a rather reasonable price of about $600 for a basic mechanical instrument that is typically used underground in the US.

The mechanical or Biram type vane anemometer is a small, windmill-like instrument consisting of a number of radial blades forming an impeller, a gearing mechanism, a clutch system, and a pointer. The blades rotate at a speed proportional to the air velocity. The gearing mechanism translates the rotation directly into linear distance and the pointer integrates the flow on a marked dial (De La Cruz, 1982).

Vane anemometer errors are categorized as those due to the design of the instrument, variations in airflow, and errors due to the operation. Errors caused by the instrument design are usually quite well managed by allowing sufficient time for measurement, typically 1 minute per reading. Variations in airflow can be avoided to some extent by choosing the measurement locations carefully. Obstructions, changes in cross-sectional area and tunnel intersections should be avoided. At less than ideal locations, measurement accuracy can be improved by performing a traverse, rather than a single point measurement (Kohler & English, 1983). However, air density differences and non-uniform air velocity distributions may also result in erroneous readings. Vane anemometers are sensitive to different measuring techniques and the proximity of the observer. It has been demonstrated that two observers with the same instrument, in the same airway, and under the same conditions may take measurements that differ by as much as 20 % (Smith, 1949; Boshkov & Wane, 1955).

Vane anemometers are incapable of measuring low air velocity due to the physical restriction of the blade rotation. Extra sensitive vane anemometers have been developed to measure low flows, but basic instruments can only measure velocity down to about 0.3 m/s (60 fpm) accurately. Correction factors for low velocity measurements with vane anemometers have been defined by Thimons *et al.* (1979).

## 2.2 Ultrasonic anemometer

Ultrasonic anemometers have been designed for measuring air velocity in three-dimensional space. It has a linear response and an absolute calibration that depends only on sensor spacing and transit time measurement accuracy. Ultrasonic pulses traveling back and forth between three sets of sensor probes are used to measure the air velocity vector.

As opposed to conventional forms of measurement this technique requires no correction for air density, it has no moving parts to wear, there is no start up friction or inertial problems when the air velocity changes rapidly and the instrument yields a linear output when calculating air velocity (Casten *et al.*, 1995). Also, the direction of the airflow can be recorded.

The instrument is robust to the surrounding environment, but physical impacts can alter the distances between the probes and affect instrument calibration. Adjustments to an instrument to correct for changes in sensor spacing can only be made by the manufacturer.

### 2.2.1 *Ultrasonic anemometer models and prices*

Ultrasonic anemometers are currently available from several manufacturers. At a minimum R. M. Young, Gill, and Vaisala have catalogs with several different ultrasonic anemometers. The typical options are basic 2-axis and 3-axis instruments designed for meteorological use. Some of the manufacturers offer heated versions for severe winter conditions and marine instruments. The prices of the basic 2-axis instruments range from below $2000 to the basic 3-axis instruments at approximately $3000. The prices of the research instruments, however, may be as high as $10,000. Gill currently offers the most extensive range of ultrasonic anemometers in the market including an intrinsically safe 2-axis instrument. More information can be found from the internet pages of the manufacturers (R. M. Young Company, 2009; Gill Instruments, 2009; and Vaisala, 2009).

EMAG in Poland has developed intrinsically safe, ultrasonic anemometers type AS-2 and AS-3 for underground use (Korczak, 2001). They are used in gassy coal mines in Poland.

# 3 Testing

## 3.1 Calibration of instruments and data acquisition

Ultrasonic anemometers were checked before and after testing at the NIOSH ventilation gallery by comparing their outputs against each other. Manufacturer calibration was performed when purchased, and there was no set schedule for regular calibration. Only when an instrument was not be within a close range to other operating anemometers in the same airflow, would it be sent to the manufacturer for recalibration.

The instruments used for testing were two 2-axis WindSonic ultrasonic anemometer and a 3-axis WindMaster ultrasonic anemometer manufactured by Gill. Both WindSonic and WindMaster instruments record flow direction and speed in the XY plane which is parallel to the mine roof and floor. Only the WindMaster gives the component of flow moving up or down through the XY plane.

Communication with the computer is via RS 232 through the computer Comm port. Data from WindSonic and WindMaster instruments is acquired through RS 422/485. The WindMaster is used with a PCI box which supplies power to the instrument and converts the RS 422/485 signal to RS 232. Telebyte converters and a separate 13 V power supply were used with the WindSonic instruments.

The ultrasonic instruments come with a software package, which can be used for data collection. Other data acquisition options include using Hyperterminal, Gill collection software, and instrument collection and control software languages like LabVIEW or MATLAB for specific software collection and development. Hyperterminal lacks a time stamp, which is available in the instruments' software package. There are no other differences in the outputs. Currently, up to 4 instruments can be used simultaneously at the NIOSH laboratory. LabVIEW compatible software is being developed to enable simultaneous data collection and real-time handling of data from up to 6 instruments.

### 3.2 Underground tests

Tests were performed underground in two locations of the NIOSH Bruceton Experimental Mine. The first location (Location 1) is in a long, straight section of a tunnel with a cross-sectional area of 5.3 $m^2$ (57 $ft^2$). The airflow was expected to be rather stable with similar fluid dynamics characteristics to a steady flow in a large tube. The second test location (Location 2) is in a curve of about 45°, so a difference in velocities was expected over the cross-section of the tunnel. The cross-sectional area of the tunnel is about 7.7 $m^2$ (83 $ft^2$). The testing locations are shown in Figure 1. Air velocity was varied in the mine by opening and closing doors and changing fan settings.

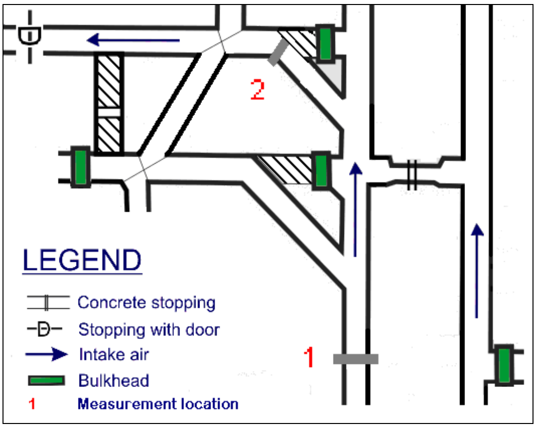

Figure 1 Underground test locations

Davis rotating vane anemometers were used to measure air velocity for anemometer comparison. Two vane anemometer traverses of 1 minute duration were taken in Location 1 with the stable airflow for each test setting and three traverses were taken in Location 2. The vane anemometer was used with an extension rod. The averages of the vane anemometer readings were compared with the results obtained by the ultrasonic anemometers.

The ultrasonic anemometer measurement duration was three minutes. However, the sample rate was one measurement per second for all the ultrasonic anemometer tests, so a total of 180 velocity values were obtained during each test.

The ultrasonic anemometers were set up in the tunnels so that the 3-axis instrument was in the middle and the 2-axis instruments were located on both sides of the 3-axis ultrasonic anemometer. The 3-axis anemometer was kept stationary throughout the measurements in both locations. 2-axis instruments were attached to adjustable poles with swinging arms. This enabled point measurements at several spots across the entry. A total of six measurements were taken across the entry with both 2-axis instruments at both locations. Figure 2 shows the ultrasonic anemometer set-up for testing in Locations 1 and 2.

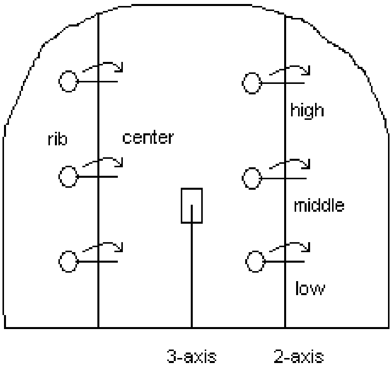

Figure 2 Instrument placing in the entry

### 3.3 Laboratory dust tests

A prior study examined factors affecting the performance of the ultrasonic anemometers in a simulated mine environment (Taylor *et al.*, 2004). During their use underground, the anemometers will be exposed to coal and rock dust (crushed limestone), which is used in coal mines to inert the atmosphere to prevent coal dust explosions. Laboratory tests were conducted at the NIOSH Pittsburgh Research Laboratory's Ventilation Test Gallery to determine what effect dust exposure would have on airflow measurements.

The effect of dust on anemometer measurements was evaluated by comparing readings from two instruments exposed to the same flows in the ventilation gallery. The readings were made in the area behind the blowing curtain (Figure 3). The test area is relatively straight with a height and width of 2.1 m (7 ft) and 0.6 m (2 ft) respectively. A wooden frame supports and maintains the shape of the curtain.

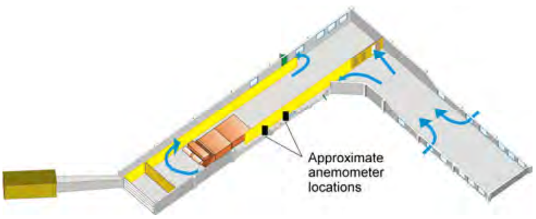

Figure 3 Ventilation Test Gallery

The two 2-axis anemometers were placed either 3 or 6.1 m (10 and 20 ft) from the end of the blowing curtain. The instrument sensor heads were positioned at the centerline of the area behind the curtain 0.3 m (12 in) from the curtain and 1.1 m (42 in) from the floor (Figure 4). The reference arrow on each instrument was pointed in the direction of the airflow and the instrument was positioned vertically using a round bubble level. With this orientation the velocity was measured for flow in a horizontal plane (Figure 5).

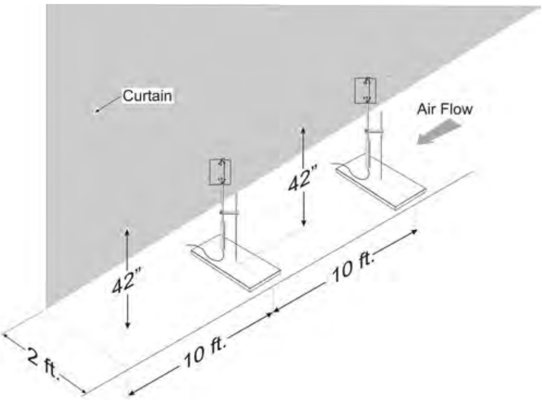

Figure 4 Instrument set-up for dust testing at the Gallery

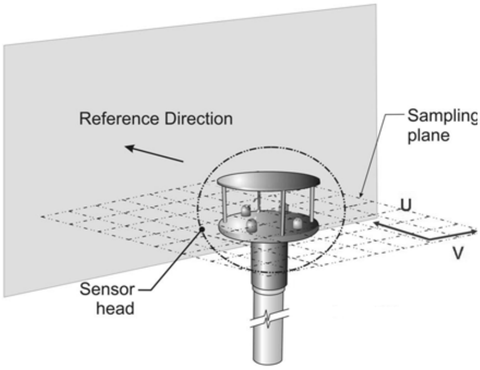

Figure 5 Orientation of anemometer sensor head

Tests were conducted with flow velocities of approximately 0.35 m/s (70 fpm), 1.75 m/s (345 fpm), and 3.10 m/s (610 fpm). The flows were adjusted by opening or closing gallery regulator doors (Figure 3). The approximate flow was monitored using a vane anemometer. Each test was repeated once and the results averaged. The instrument positions were reversed and two additional tests were conducted. The results of the four tests were averaged for each velocity.

Either coal dust or rock dust was applied to sensor heads of the test instrument. The two dusts were similar with respect to particle size. Approximately 75% of each dust passed through a 200 mesh sieve. One instrument was kept clean at all times for comparison purposes.

First the dust was applied to the tops of the sensors using a spatula. The instrument was then held horizontal with sensor head tilted 90° and tapped lightly to remove excess dust. For one test set with both coal dust and rock dust the sensor heads were first sprayed with water before applying the dust. Again the excess dust was discarded by holding the instrument horizontal. The resulted dust layer for coal dust is shown in Figure 6. Also, testing was performed without dumping the excess dust off to evaluate the effect of dust piling on the instruments (Figure 7).

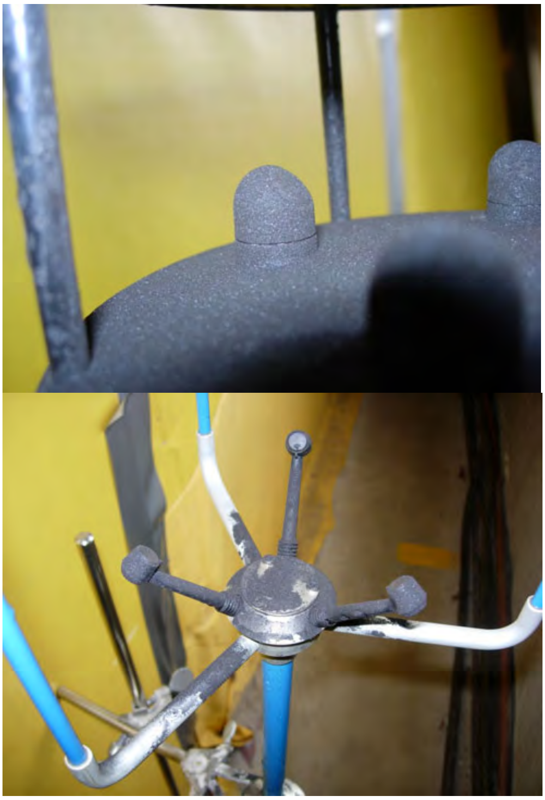

Figure 6 Wetted coal dust on 2-axis and 3-axis ultrasonic anemometer heads

Figure 7 Dry rock dust piled on the 2-axis instrument.

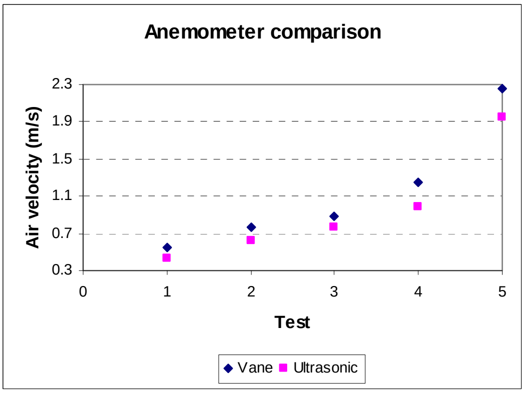

Figure 8 Comparison of vane and ultrasonic anemometer measurement results with different airflows

# 4 Results

## 4.1 Underground tests

The point measurement results taken over a cross-section with the ultrasonic anemometers were averaged for comparison with the averaged vane anemometer results. The results from the ultrasonic anemometer and rotating vane anemometer comparison show that higher air velocity values were measured with vane anemometer in Locations 1 and 2 than with the ultrasonic anemometers. The recorded differences shown in Figure 8 ranged from about 0.1 m/s (20 fpm) to 0.3 m/s (60 fpm) showing larger differences with higher air velocities. This correlates well with prior results from Casten *et al*. (1995) who stated that a Gill 3-axis anemometer tended to underestimate the air velocity when compared to a Davis rotating vane anemometer.

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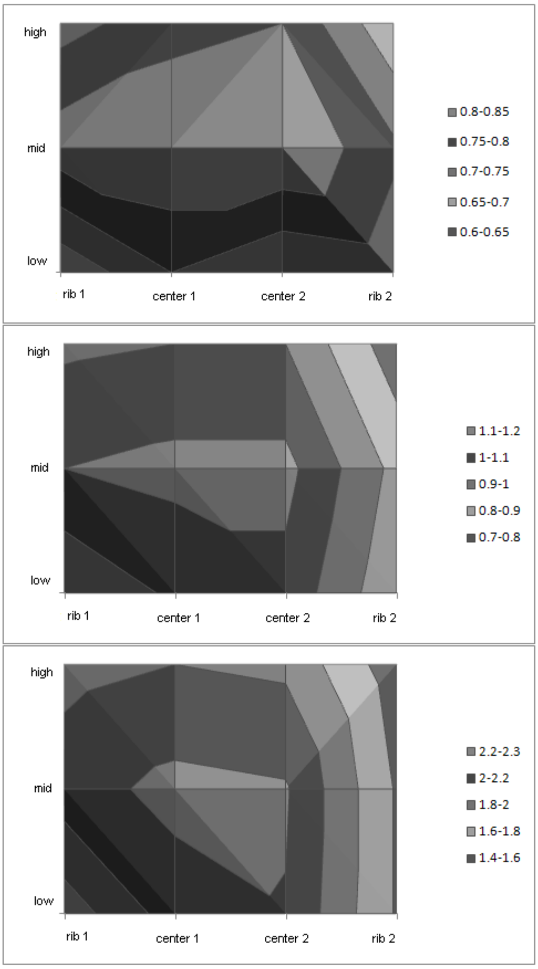

Figure 9 Air velocity contours at Location 1

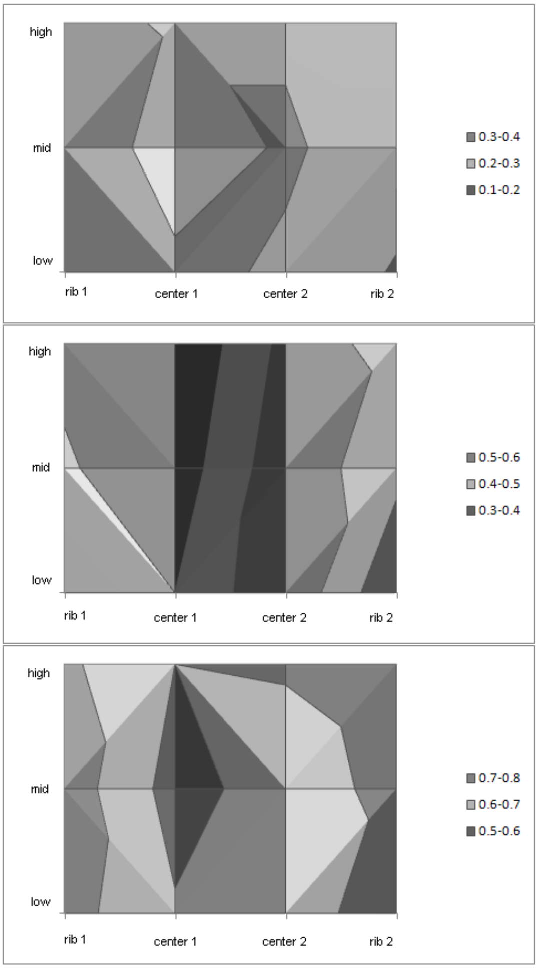

Figure 10 Air velocity contours at Location 2

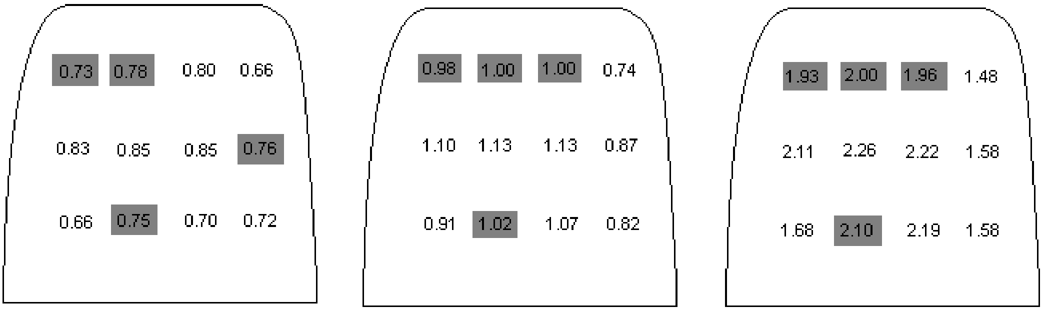

Figure 11 Air velocity values closest to the average over the cross-section in Location 1 (Straight airway)

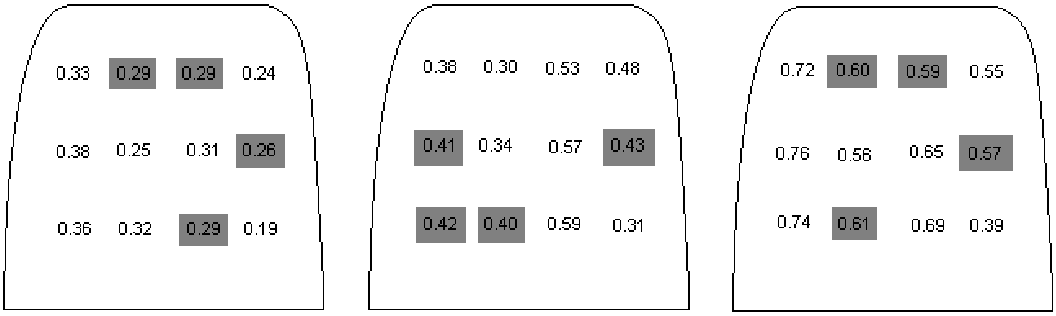

Figure 12 Air velocity values closest to the average over the cross-section in Location 2 (Curved airway)

Both 2- and 3-axis ultrasonic anemometers performed well even at rather low air velocities. In Location 2, the average air velocity of the lowest airflow was 0.29 m/s measured with the ultrasonic anemometer. At this velocity the vane anemometer refused to work properly.

Defining the optimal location for measuring air velocity in an entry is important. The instrument should be able to detect an air velocity as close to the average velocity over the cross-section of the entry as possible. For location analysis, the results of the three different velocities at the two locations were evaluated. Average velocities in Location 1 were 0.76, 0.99 and 1.95 m/s and in Location 2 they were 0.29, 0.43 and 0.61 m/s. Twelve 2-axis ultrasonic anemometer measurements (Figure 2) were taken over the cross-section in both locations.

In Location 1, the straight tunnel, the results showed the expected flow pattern similar to a flow in a tube with the highest velocity in the center. However, the distribution of the flow was not as stable as in a tube due to the rough walls and corner areas. In Location 2, the curve, the airflow was non-uniform with higher airflows in two areas. The velocity measurements were taken at Location 1 0.4 m (14 in), 1.1 m (44 in), 1.5 m, (58 in) and 2.6 m (102 in) from left rib and at Location 2 approximately 0.2 m (7 in), 0.9 m (37 in) and 2.9 m (114 in) and 3.9 m from left rib. Measurement heights were 0.6 m (2 ft), 1.2 m (4 ft) and 1.6 m (5 ft 6 in) in both locations. Approximate air velocity contours (not to scale) are shown in Figures 9 & 10. Three-axis anemometer readings, taken in the middle were used to confirm the 2-axis anemometer results closest to the center of the entry.

The average values recorded during the 3 minute sampling in each of the 12 locations were compared with the average air velocity over the cross-section. The four values out of twelve (33%) closest to the overall average were then identified. In Location 1 it was noticed that the location of these close-to-average values was comparable through all three different air velocities (Figure 11). In Location 2, the situation was more complicated with the close-to-average value locations spread over the cross-section in a different pattern for each velocity (Figure 12).

It can be seen from the results that taking a centerline reading will result in a higher than average value in a straight tunnel. The air velocity contours are comparable to airflow in a duct with zero velocity against the walls of the duct and the highest velocity in the middle (Cheremisinoff & Gupta, 1983). Average values are to be expected at about ¼D from the duct walls in case of laminar flow. In a mine the openings may be more rectangular. In this situation the hydraulic diameter, $D_H$, can be used to locate the average velocity. The average velocity occurs approximately at ¼$D_H$ from the ribs, floor, and ceiling of a rectangular tunnel with a laminar flow (Ebadian & Dong, 1998).

### 4.2 Laboratory dust tests

The dust exposure testing showed a small decrease in the measured velocity after application of dust with or without water in almost all cases. Wet rock dust caked on the instrument was found to result in instrument signal interruptions. Consequently, the wetted rock dust results were left out from the velocity difference analysis. The results with wet and dry coal dust and dry rock dust are shown in Figure 13.

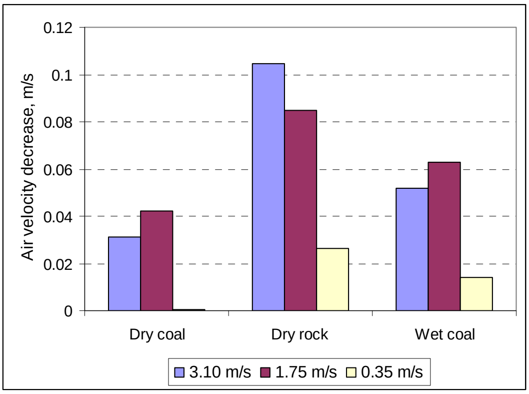

Figure 13 Velocity decrease with wet and dry dusts

To test the effect of piling of dust, coal dust or rock dust was added to the tops of the sensors until there was loss of signal and no more velocity data was generated. At this point the instrument generated an error code. The manufacturer said that when the dust deposit reaches a critical thickness where it is attenuating the ultrasonic signals too much for the anemometer to compensate for, an error code is shown. The measurement results should be accurate as long as no error codes are being reported. In case of an error code a simple cleaning, such as wiping the sensor down with a wet cloth or even blowing some air to remove dust from the sensor should be sufficient to return the sensor to good working condition (Doyle, 2009). In these tests, brushing the sensor head lightly was found to work best in removing the dust. Data generation resumed after cleaning and velocity readings were approximately the same as before application of dust. In practice, the recorded air velocity decreases are so small, that before loss of signal, the results can be considered accurate enough for underground air velocity screening.

## 5 Conclusions

Ultrasonic anemometers can be used underground for air velocity screening purposes. It is recommended that for a permanent underground installation a location analysis be made to enable collection of representative velocity values. Point measurements should be taken at several locations over the cross-section and their average calculated. The location giving closest values to the average should be selected for ultrasonic anemometer measurements. In case of a straight tunnel with a similar width and height a good approximation is flow in a circular duct. Average values are acquired at ¼D of the duct walls. In case of a rectangular opening, hydraulic diameter $D_H$ can be used for the approximation. For more complicated tunnel shapes, tunnels with obstructions, and curved locations flow simulation is recommended to find the optimal location.

Comparison of vane anemometer and ultrasonic anemometer values showed that vane anemometer readings were higher than the results obtained with ultrasonic instruments. This correlates well with a previous study. Even so, the reason for the difference is questioned as ultrasonic anemometers are considered very accurate and this will be studied in the future.

It was observed that coal dust was easy to clean off of the instrument even when wet and it did not pile up to a critical thickness easily. Rock dust, on the other hand, tended to cake on the instrument due to its hygroscopic behaviour. Even when added on the instrument dry, it resulted in the largest reduction in air velocity. Regular cleaning of the instrument is expected to be needed in a humid, dusty environment to keep it in working order.

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## Disclaimer

The findings and conclusions in this manuscript are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by NIOSH.

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