Chapter 6. Ventilation Surveys

6.1. PURPOSE AND SCOPE OF VENTILATION SURVEYS

6.2. AIR QUANTITY SURVEYS

6.2.1. Rotating vane anemometers
6.2.2. Moving Traverses

6.2.3. Fixed point measurement
6.2.4. Density correction
6.2.5. Swinging vane anemometer (velometer)
6.2.6. Vortex-shedding anemometer
6.2.7. Smoke tubes
6.2.8. Pitot-static tube
6.2.9. Fixed point traverses

6.3. PRESSURE SURVEYS

6.3.1. Gauge and tube surveys
6.3.2. Barometer and altimeter surveys

6.4. ORGANIZATION OF PRESSURE-VOLUME SURVEYS

6.5. AIR QUALITY SURVEYS

BIBLIOGRAPHY

APPENDIX A6
Application of the gauge and tube method of measuring frictional pressure drops in cases of significant differences in elevation
6.1. PURPOSE AND SCOPE OF VENTILATION SURVEYS

A ventilation survey is an organized procedure of acquiring data that quantify the distributions of airflow, pressure and air quality throughout the main flowpaths of a ventilation system. The required detail and precision of measurement, and the rigour of the ensuing data analysis depend upon the purpose of the survey. Perhaps the most elementary observation in underground ventilation is carried out by slapping one's clothing and watching the dust particles in order to ascertain the direction of a sluggish airflow.

Measurements of airflow should be taken in all underground facilities at times and places that may be prescribed by law. Even in the absence of mandatory requirements, a prudent regard for safety indicates that sufficient routine measurements of airflow be taken
(a) to ensure that all working places in the mine receive their required airflows in an efficient and effective manner,
(b) that ventilation plans are kept up to date and
(c) to verify that the directions, quantities and separate identity of airflows throughout the ventilation infrastructure, including escapeways, are maintained.

Similarly, routine measurements of pressure differentials may be made across doors, stoppings or bulkheads to ensure they are also maintained within prescribed limits and in the correct direction. The latter is particularly important in underground repositories for toxic or nuclear materials and where spontaneous combustion may occur.

One of the main differences between a mine ventilation system and ductwork in a building is that the mine is a dynamic entity, changing continuously due to modifications to the structure of the network and resistances of individual branches. Regular measurements of airflow and pressure differentials underground are necessary as a basis for incremental adjustment of ventilation controls.

During the working life of a mine or other underground facility, there will be occasions when major modifications are required to be made to the ventilation system. These circumstances include opening up new districts in the mine, closing off older ones, commissioning new fans or shafts, or interconnecting main sections of the mine. The procedures of ventilation planning are detailed in Chapter 9. It is important that planning the future ventilation system of any facility is based on reliable and verified data. Ventilation surveys that are carried out in order to establish a data base for planning purposes must necessarily be conducted with a higher degree of organization, detail and precision than those conducted for routine monitoring and control. This chapter is directed primarily towards those more accurate surveys.

A major objective of ventilation surveys is to obtain the frictional pressure drop, \( p \), and the corresponding airflow, \( Q \), for each of the main branches of the ventilation network. From these data, the following parameters may be calculated for the purposes of both planning and control:

- distribution of airflows, pressure drops and leakage
- airpower \((p \times Q)\) losses and, hence, distribution of ventilation operating costs throughout the network (Section 9.5.4)
- volumetric efficiency of the system (Section 4.2.3)
- branch resistances \((R = p/Q^2)\)
- natural ventilating effects
- friction factors (Equation 5.11)

While observations of airflow and pressure differentials are concerned with the distribution and magnitudes of air volume flow, other measurements may be taken either separately or as an integral part of a pressure/volume survey in order to indicate the quality of the air. These measurements may include wet and dry bulb temperatures, barometric pressures, dust levels and concentrations of gaseous pollutants.
6.2 AIR QUANTITY SURVEYS

The volume of air, \( Q \), passing any fixed point in an airway or duct every second is normally determined as the product of the mean velocity of the air, \( u \), and the cross-sectional area of the airway or duct, \( A \)

\[
Q = u \times A
\]

\[
\frac{m}{s} \times m^2 = \frac{m^3}{s}
\]

Most of the techniques of observing airflow are, therefore, combinations of the methods available for measuring mean velocity and cross-sectional area.

Prior to the invention of anemometers in the nineteenth century, the only practicable means of measuring rates of airflow in mines was to observe the velocity of visible dust or smoke particles suspended in the air. An even cruder old method was to walk steadily in the same direction as the airflow, varying one's pace, until a candle flame appeared to remain vertical. Modern instruments for the measurement of airspeed in mines divide into three groups depending upon (i) mechanical effects, (ii) dynamic (velocity) pressure of the airflow and (iii) thermal effects.

6.2.1. Rotating vane anemometers

The vast majority of airspeed measurements made manually underground are gained from a rotating vane (windmill type) anemometer. When held in a moving airstream, the air passing through the instrument exerts a force on the angled vanes, causing them to rotate with an angular velocity that is closely proportional to the airspeed. A gearing mechanism and clutch arrangement couple the vanes either to a pointer which rotates against a circular dial calibrated in meters (or feet) or to a digital counter.

The instrument is used in conjunction with a stopwatch and actually indicates the number of "metres of air" that have passed through the anemometer during a given time period. The clutch device is employed to stop and start the pointer or digital counter while the vanes continue to rotate. A zero reset lever is also incorporated into the instrument. Low range vane anemometers will typically have eight vanes, jewelled bearings and give repeatable readings for velocities in the range 0.25 to 15 m/s. High range instruments may have four vanes, low-friction roller or ball bearings and can be capable of measuring air velocities as high as 50 m/s. Digital vane anemometers indicate directly on an odometer counter, an illuminated screen, or feed an electronic signal into a data gathering system. Modern handheld instruments may also be fitted with a microprocessor to memorize readings, dampen out rapid variations in velocity or into which can be entered the cross-sectional area for the calculation of volume flow. Two types of vane anemometer are included in the selection of ventilation survey instruments shown on Plate 1.

In order to obtain a reliable measure of the mean air velocity in an underground airway, it is important that a recommended technique of using the anemometer is employed. The following procedure has evolved from a combination of experiment and practical experience.

6.2.2. Moving Traverses

The anemometer should be attached to a rod of at least 1.5m in length, or greater for high airways. The attachment mechanism should permit the options of allowing the anemometer to hang vertically or to be fixed at a constant angle with respect to the rod. A rotating vane anemometer is fairly insensitive to yaw and will give results that do not vary by more than ±5 per cent for angles deviating by up to 30° from the direction of the airstream. Hence, for most
underground airways, allowing the anemometer to hang freely at the end of the rod will give acceptable results. For airways of inclination greater than 30°, the anemometer should be clamped in a fixed position relative to the rod and manipulated by turning the rod during the traverse such that the instrument remains aligned with the longitudinal axis of the airway.

The traverse
The observer should face into the airflow holding the anemometer rod in front of him/her so that the dial is visible and at least 1.5m upstream from his/her body. To commence the traverse, the instrument should be held either in an upper or lower corner of the airway, with the pointer or counter reset to zero, until the vanes have accelerated to a constant velocity. This seldom takes more than a few seconds. The observer should reach forward to touch the clutch control lever while a second observer with a stopwatch counts backwards from five to zero. On zero, the anemometer clutch is activated releasing the pointer and, simultaneously, the stopwatch is started.

The path of the traverse across the airway should be similar to that shown on Figure 6.1. The aim should be to traverse the anemometer at a constant rate not greater than about 15 per cent of the airspeed. Ideally, equal fractions of the airway cross sectional area should be covered in equal times. This is facilitated by the stopwatch observer calling out the elapsed time at ten second intervals. The complete traverse should take not less than 60 seconds and may be considerably more for large or low velocity airways. The final five seconds should be counted down by the stopwatch observer during which time the traverse person stretches forward to disconnect the clutch at the end of the time period. The length indicated by the anemometer is immediately read and booked, and the instrument reset to zero.
The procedure is repeated, traversing in the opposite direction across the airway. Traverses should be repeated until three readings are obtained that agree to within ± 5 per cent. In favourable steady state conditions, experienced observers will often achieve repeatability to within ± 2 per cent. Larger discrepancies may be expected in airways where there is a highly asymmetric variation in velocity across the airway, where the floor conditions are unstable, or when obstructions exist in the cross section. Measuring stations should be chosen to avoid such difficulties wherever possible. Another annoying cause of discrepancy is the opening of a ventilation door during the period of measurement. Two or more sets of traverses should be taken at different locations within each airway. Where cross-cuts or other leakage paths affect the airflow then a sufficient number of additional measurement points should be traversed in order to quantify the rate and direction of leakage.

Booking
The anemometer field book should be waterproof and laid out such that each double page has segments for

1. names of observers
2. the location of the measuring station, time, date,
3. anemometer readings and corrections
4. dimensioned sketch of cross-section
5. calculation of area
6. calculation of air volume flow.
The bookings are normally made by the stopwatch person. For each traverse, the anemometer reading is divided by the corresponding time to give the air velocity. The mean of these station velocities, ignoring any values outside the ±5 per cent tolerance, gives the observed mean velocity. In most cases, the time of each traverse at a station is the same, allowing the anemometer readings to be averaged before calculating the mean velocity. The observed mean velocity must then be corrected according to the calibration chart or curve for the instrument (Section 6.4) to give the actual mean velocity, $u$.

The cross-sectional area, $A$, is determined using one of the methods discussed in section 6.2.12. The calculation of airflow is then completed as

$$Q = u \times A = \frac{m}{s} \times m^2 = \frac{m^3}{s}$$

Anemometer traverses may also be employed at the ends of ducts. However, it is recommended that the technique not be used for duct diameters less than six times that of the diameter of the anemometer.

### 6.2.3. Fixed point measurement

An estimate of duct airflow may be obtained by holding the anemometer at the centre of the duct and multiplying the corrected reading by a further correction factor of 0.8. A similar technique may be employed for routine check readings taken at well-established measuring stations in airways. The reading obtained from a stationary anemometer at a known location within the cross-section should, initially, be compared with that given from a series of traverses in order to obtain a "fixed point" correction factor for that station. This is typically 0.75 to 0.8 for the fixed point located some one half to two thirds the height of the airway. Subsequent routine readings may be obtained simply by taking an anemometer reading at the fixed point and applying the appropriate calibration and fixed point corrections. Provided that the measuring station is well downstream of any bends or major obstructions and the airflow remains fully turbulent then the fixed point correction factor will stay near constant as the airflow varies.

### 6.2.4. Density correction

For precise work, anemometer readings may be further corrected for variations in air density:

$$u = u_i + C_c \sqrt{\frac{\rho_c}{\rho_m}}$$

where
- $u$ = corrected velocity
- $u_i$ = indicated velocity
- $C_c$ = correction from instrument calibration curve or chart
- $\rho_c$ = air density at time of calibration
- $\rho_m$ = actual air density at time of measurement

Equation (6.1) shows that the density adjustment $\sqrt{\frac{\rho_c}{\rho_m}}$ is effectively applied only to the calibration correction and is ignored in most cases.

### 6.2.5. Swinging vane anemometer (velometer)

In its most fundamental form, the swinging vane anemometer (velometer) is simply a hinged vane which is displaced against a spring from its null position by a moving airstream. A connected
pointer gives a direct reading of the air velocity. The air enters a port at the side of the instrument. This port can be fitted with interchangeable orifices or probes to give a range of measurable velocities. Oscillations of the vane may be reduced by the eddy current damping produced when a metal strip connected to the vane moves between strong permanent magnets. The delicacy of the velometer together with its pronounced directional bias has limited its use in underground surveys. However, it can serve a useful purpose in giving spot readings as low as 0.15 m/s in gassy mines where hot wire probes are prohibited.

6.2.6. Vortex-shedding anemometer

For continuous monitoring systems, both rotating vane and swinging vane instruments with electrical outputs have been employed. However, they both require relatively frequent calibration checks when used in mine atmospheres. For this type of application, the vortex-shedding anemometer is preferred as it has no moving parts.

When any bluff object is placed in a stream of fluid, a series of oscillating vortices are formed downstream by boundary layer breakaway, first from one side of the body then the other. The propagation of the vortices is known as a Kármán street and can often be observed downstream from projecting boulders in a river. The rate of vortex production depends upon the fluid velocity. In the vortex-shedding anemometer, the vortices may be sensed by the pulsations of pressure or variations in air density that they produce. One apparent disadvantage noticed in practice is that when sited in a fixed location underground for monitoring purposes they require calibration for that specific location. They may also require electronic damping to eliminate large but short lived variations in signals caused by the passage of vehicles.

6.2.7. Smoke tubes

Smoke tubes are perhaps the simplest of the mechanical techniques employed for measuring airflows and are used for very low velocities. A pulse of air forced by a rubber bulb through a glass phial containing a granulated and porous medium soaked in titanium tetrachloride or anhydrous tin will produce a dense white smoke. This is released upstream of two fixed marks in the airway. An observer with a spot-beam cap lamp is located at each mark. The time taken for the cloud of smoke to travel the length of airway between the marks gives an indication of the centre-line velocity of the air. This must then be adjusted by a centre-line correction factor to give the mean velocity. The correction factor is usually taken to be 0.8 although a more accurate value can be calculated for known Reynold's numbers. The length of airway should be chosen such that at least one minute elapses during the progression of the smoke between the two marks. Dispersion of the smoke cloud often causes the downstream observer some difficulty in deciding when to stop the stopwatch. Due to the uncertainties inherent in the technique, smoke tubes are normally employed as a last resort in slow moving airstreams.

6.2.8. Pitot-static tube

In section 2.3.2 we discussed the concepts of total, static and velocity pressures of a moving stream of fluid. A pitot-static tube, illustrated on Figure 6.2, can be used to measure all three. This device consists essentially of two concentric tubes. When held facing directly into an airflow, the inner tube is subjected to the total pressure of the moving airstream, \( p_t \). The outer tube is perforated by a ring of small holes drilled at right angles to the shorter stem of the instrument and, hence, perpendicular to the direction of air movement. This tube is, therefore, not influenced by the kinetic energy of the airstream and registers the static pressure only, \( p_s \). A pressure gauge or manometer connected across the two tappings will indicate the difference between the total and static pressure, i.e. the velocity pressure:

\[
p_v = p_t - p_s \quad \text{Pa} \quad \text{[ from equation (2.18) ]} \quad (6.2)
\]
Furthermore, the velocity head is related to the actual velocity of the air, \( u \)

\[
u = \sqrt{\frac{2p_v}{\rho}} \quad \text{m/s} \quad \text{[from equation (2.17)]} \quad (6.3)
\]

where

\[
\rho = \text{actual density of the air (} \text{kg/m}^3)\n\]

(see equation (14.52) for air density).

Pitot-static tubes vary widely in overall dimensions. For measuring air velocities in mine airways or at main fans, the longer stem may be some 1.5m in length. Much smaller versions are available for use in ducts or pipes.

Modern pitot-static tubes reflect the total, static and velocity pressures of the airflow to an excellent degree of accuracy. Unfortunately, the precision of the measurement depends also upon the manometer or pressure gauge connected to the tappings. This imposes a practical restriction on the lower limit of air velocity that can be measured by a pitot-static tube in the turbulent airflows of an underground system.
Example

If a diaphragm pressure gauge can be read to the nearest ± 1 Pa, then the lowest pressure that will give 10 per cent accuracy in the pressure reading is 10 Pa. Calculate the air velocity corresponding to a velocity pressure of 10 Pa, assuming an air density of 1.2 kg/m³.

Solution

\[ u = \sqrt{\frac{2 \times p_v}{\rho}} = \sqrt{\frac{2 \times 10}{1.2}} = 4.08 \text{ m/s} \]

As the great majority of underground openings have air velocities of less than 4 m/s, it is clear that the use of the pitot-static tube for the measurement of air velocity is limited to ventilation ducting and a few high velocity airways; primarily fan drifts and evasees, ventilation shafts, some longwall faces and trunk airways.

One of the difficulties of using a pitot-static tube for the spot measurement of pressures or velocities in a turbulent airstream is the oscillation in the readings. A small wad of cotton wool inserted into the flexible pressure tubing between the pitot-static tube and the pressure gauge damps out the short term variations. However, the cotton wool should not be so tightly tamped into the tubing that the gauge reaction becomes unduly slow. Electronic diaphragm gauges are often fitted with an internal damping circuit.

6.2.9. Fixed point traverses

The rotating vane anemometer is an integrating device, accumulating the reading as it is traversed continuously across an airway or duct. Most other instruments for the measurement of air velocity, including the pitot-static tube, do not have this advantage but are confined to giving a single spot reading at any one time. In order to find the mean velocity in an airway from pitot-static tube readings it is, therefore, necessary to take spot measurements at a number of locations over the cross-section. This procedure is known by the contradictory sounding term “fixed point traverse”. Differing techniques of conducting such traverses vary in the number of observations, locations of the instrument and treatment of the data. Three of these techniques are described here. In all cases, the fixed point traverse method assumes that the distribution of flow over the cross-section does not vary with time. For permanent monitoring stations, a grid of multiple pitot-static tubes may be left in place.

Method of equal areas

In this method, the cross-section of the duct or airway is divided into subsections each of equal area. Figure 6.3 shows a rectangular opening divided into 25 equal subsections similar in shape to the complete opening. Using a pitot-static tube or anemometer, the velocity at the centre of each subsection is measured. The mean velocity is then simply the average of the subsection velocities.

There are a few precautions that should be taken to ensure satisfactory results. First, if a pitot-static tube is employed then the velocity at each subsection should be calculated. Averaging the velocity pressure before employing equation (6.3) will not give the correct mean velocity. Secondly, it will be recalled that the velocity gradient changes most rapidly near the walls. Hence, accuracy will be improved if the velocities for the subsections adjacent to the walls and, especially, in the corners are determined from a number of readings distributed within each of those subsections. Third, the number of subsections should increase with respect to the size of the airway in order to maintain accuracy.
As a guide, the recommended number of points, \( n \), for a rectangular opening may be estimated as

\[
n = 100 \, e^{\frac{8}{A}} + 23
\]

(6.4)

where \( e \) is the exponential exponent, 2.7183 and

\( A \) is the cross-sectional area \( \text{m} \)

The estimated number of points may then be rounded to a value that is convenient for subdividing the cross-sectional area but should never be less than 24. Correct positioning of the measuring instrument is facilitated by erecting a grid of fine wires in the airway to represent the subsections.

In the case of circular openings, the method of equal areas divides the circle into annuli, each of the same area. Readings should be taken at points across two diameters and the corresponding velocity profiles plotted. Should those profiles prove to be skewed then readings should be taken across two additional diameters. The number of measuring points recommended on each diameter is given in Table 6.1. Figure 6.4 illustrates an 8 point traverse on each of 4 diameters.

<table>
<thead>
<tr>
<th>Diameter of duct (m)</th>
<th>&lt; 1.25</th>
<th>1.25 - 2.5</th>
<th>&gt; 2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of points</td>
<td>6</td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 6.1 Number of measuring points on each diameter of a circular opening.
Chapter 6. Ventilation Surveys

The locations of the points are at the centre of area of the relevant annulus on each diameter and may be calculated from

\[ r = D \frac{2n-1}{4N} \quad \text{m} \quad (6.5) \]

where

- \( r \) = radius of point \( n \) from the centre
- \( n \) = number of the point counted outwards from the centre
- \( D \) = diameter of the duct (m)
- \( N \) = number of points across the diameter

Table 6.2 gives locations of points for 6, 8, and 12 point traverses in terms of fractions of duct diameter measured from one side.

Where a pitot-static tube traverse is to be conducted across a duct from the outside then a clamping device should be attached to the outer surface of the duct to hold the pitot-static tube firmly in place. The positions of measurement should be marked on the stem of the instrument.
using Table 6.2 or 6.3. After each relocation of the measuring head, the pitot-static tube should be yawed slightly from side to side until the orientation is found that gives the greatest reading of total or velocity pressure. The head of the instrument is then aligned directly into the airstream.

<table>
<thead>
<tr>
<th>No. of measuring points on each diameter</th>
<th>Fractions of one diameter measured from side of duct</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>centre</td>
</tr>
<tr>
<td>6</td>
<td>0.044 0.146 0.296 0.704 0.854 0.956</td>
</tr>
<tr>
<td>8</td>
<td>0.032 0.105 0.194 0.323 0.677 0.806 0.895 0.968</td>
</tr>
<tr>
<td>12</td>
<td>0.021 0.067 0.118 0.250 0.356 0.644 0.750 0.823 0.882 0.933 0.979</td>
</tr>
</tbody>
</table>

Table 6.2  Positions of measuring points in a circular duct using the method of equal areas.

*Log-linear traverse*

A more accurate method of positioning points of measurement along the diameters of a circular duct has been derived from a consideration of the logarithmic law equations that describe the velocity profile for turbulent flow. The effects of observational errors are minimized when the points are located according to this method, known as the log-linear traverse. The corresponding locations are given in Table 6.3.

<table>
<thead>
<tr>
<th>No. of measuring points on each diameter</th>
<th>Fractions of one diameter measured from side of duct</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>centre</td>
</tr>
<tr>
<td>6</td>
<td>0.032 0.135 0.321 0.679 0.865 0.968</td>
</tr>
<tr>
<td>8</td>
<td>0.021 0.117 0.184 0.345 0.655 0.816 0.883 0.978</td>
</tr>
<tr>
<td>12</td>
<td>0.014 0.075 0.114 0.183 0.241 0.374 0.626 0.759 0.817 0.886 0.925 0.986</td>
</tr>
</tbody>
</table>

Table 6.3  Log-linear traverse positions of measuring points in a circular duct.

*Velocity contours*

One of the difficulties that besets ventilation engineers in measuring large scale airflows is that conditions are often not conducive to good accuracy. "Textbook" advice is to choose measuring stations well away from obstructions, bends or changes in cross-section. Unfortunately, this is not always possible, especially when measuring airflows at the inlets or outlets of fans. It is not uncommon to find that longitudinal swirl in a fan drift or re-entry in an evasee causes the air to move in the wrong direction within one part of the cross-section. Similarly, in obstructed but high velocity airways underground such as many longwall faces, complex airflow patterns may exist.
A useful rule of thumb is that the averaging of spot velocities from a pitot-static tube traverse is acceptable if more than 75 per cent of the velocity pressures \( (p_v) \) are greater than the maximum \( p_v \) divided by 10.

For difficult cases, the construction of velocity contours can provide both a visual depiction of the flow pattern and also a means of quantifying airflow. A scale drawing of the measurement cross-section is made on graph paper. A grid of fine wires is constructed in the airway to define the points of measurement. The number of points should be not less than that recommended in the previous subsection. The greater the number of measurement points, the more accurate will be the result. The velocities at the corresponding points of measurement are entered on the graph paper and contour lines of equal velocity (isovels) are constructed. Figure 6.5 shows an example of velocity contours obtained on a longwall face.

![Example of velocity contours at an airflow measuring station on a longwall face](image.png)

The area enclosed by each contour can be determined either by planimeter (if the scale drawing is large enough for good planimeter accuracy) or by the rudimentary method of counting squares on the graph paper. The construction of isovels and determination of the areas enclosed are greatly facilitated by the use of a computer software contouring package. Fully automated systems have been devised that scan the actual cross-section and produce quantified velocity contour diagrams. However, the expense of such systems is seldom justified other than in research and testing laboratories.

By difference, the area of the band between each contour is evaluated and may be multiplied by the mean of the bounding velocities and the area scale factor to give the airflow for that band. Provided that the outermost contour is close to the walls then the velocity at the walls may be taken as zero. The sum of all band airflows gives the total flow for the airway.

6.2.10 Hot body anemometers

When any heated element is placed in a moving fluid, heat energy will be removed from it at a rate that depends upon the rate of mass flow over the element.

In the hot wire anemometer a wire element is sited within a small open ended cylinder to give the instrument a directional bias. The element forms one arm of a Wheatstone bridge circuit. In most hot wire anemometers, the temperature of the element is maintained constant by varying the
electrical current passing through it as the air velocity changes. In other designs, the current is kept constant and the temperature (and, hence, electrical resistance) of the element is monitored. Modern hot wire anemometers are compensated for variations in ambient temperature and most also indicate dry bulb temperature. For precise work, readings should be corrected for air density:

\[ u = \frac{u_i \rho_c}{\rho_m} \]  

(6.5)

where

- \( u \) = true air velocity
- \( u_i \) = indicated air velocity
- \( \rho_c \) = air density at calibration (usually 1.2 kg/m\(^3\))
- \( \rho_m \) = actual air density at time of measurement.

Hot wire anemometers are particularly useful for low velocities and are reliable down to about 0.1 m/s. They are convenient for fixed point traverses in slow moving airstreams. If a hot wire anemometer is to be used in a gassy mine then a check should first be made on the permissibility of the instrument for use in potentially explosive atmospheres.

The Kata thermometer, described in Section 17.4.3.2 as a means of measuring the cooling power of an airstream, can also be used as a non-directional device to indicate low air velocities, typically in the range 0.1 to 1 m/s. The main bulb of the Kata thermometer is heated until the alcohol level is elevated above the higher of the two marks on the stem. When hung in an airstream, the time taken for the alcohol level to fall between the two marks, coupled with the Kata index for the instrument and the air temperature, may be used to determine the non-directional air velocity. The Kata thermometer is seldom used for underground work (except in South Africa) because of its fragility.

6.2.11. Tracer gases

The rate at which injected gases are diluted provides a means of measuring air volume flow without the need for a cross-sectional area. The method is particularly useful for difficult situations such as leakage flow through waste areas, main shafts and other regions of high velocity and excessively turbulent flow, or total flow through composite networks of airways.

Hydrogen, nitrous oxide, carbon dioxide, ozone, radioactive krypton 85 and sulphur hexafluoride have all been used with the latter particularly suitable for leakage or composite flows. The gas chosen should be chemically inert with respect to the mineralization of the strata.

There are two techniques of using tracer gases for the measurement of airflow. For high velocity airways, the tracer gas may be released at a monitored and steady rate \( M_g \) (kg/s). At a point sufficiently far downstream for complete mixing to have occurred, samples of the air are taken to establish the steady state concentration of the tracer gas. Then

\[ C = \frac{q_g}{Q} = \frac{M_g}{\rho_g Q} \]  

or

\[ Q = \frac{M_g}{C \rho_g} \]  

(6.7)

where

- \( q_g \) = volume flow of tracer gas (m\(^3\)/s)
- \( Q \) = airflow (m\(^3\)/s)
- \( C \) = downstream concentration of tracer gas (fraction by volume)
- \( \rho_g \) = density of tracer gas at ambient pressure and temperature (kg/m\(^3\))

It is assumed that the volume flow of tracer gas is negligible compared with the airflow.
In the case of sluggish or composite flows, a known mass of the tracer gas, $M$ (kg), is released as a pulse into the upstream airflow. At the downstream station, the concentration of tracer gas is monitored and a concentration-time, ($C \times t$), graph is plotted as shown on Figure 6.6. Now, the concentration $C$ is given as the ratio of the volume flow rate of gas, $q_g$, and the airflow, $Q$.

$$C = \frac{q_g}{Q} \quad \text{(fraction, by volume)}$$

But

$$q_g = \frac{M_g}{\rho_g} \quad \text{m}^3 \text{s}^{-1}$$

where $M_g = \text{mass flow rate of gas at the monitored downstream station (kg/s)}$
and $\rho_g = \text{density of gas at the prevailing temperature and pressure kg/m}^3$

giving

$$C = \frac{M_g}{\rho_g \cdot Q}$$

Figure 6.6  Concentration-time curve at a tracer gas monitoring station
Hence, the complete area under the curve of $C$ against $t$,

$$ I = \int_{0}^{\infty} C \, dt \quad \text{(This equals the total volume of tracer gas that passed the station)} $$

$$ = \frac{1}{\rho_{g} Q} \int_{0}^{\infty} M_{g} \, dt $$

But the total mass of gas released, $M$, must also be equal to $\int_{0}^{\infty} M_{g} \, dt$ (assuming that all of the air passing the upstream station also passes through the downstream station).

giving

$$ I = \frac{M}{\rho_{g} Q} $$

or

$$ Q = \frac{M}{I \rho_{g}} \quad \frac{m^{3}}{s} \quad (6.8) $$

### 6.2.12 Measurement of cross-sectional area

As the vast majority of airflows are determined as the product of a mean velocity and a cross-sectional area, the accuracy of the airflow depends equally upon the measured velocity and cross-sectional area. There is little point in insisting upon meticulous procedures for the measurement of mean velocity unless the same care is applied to finding the cross-sectional area.

By far the most common method of measuring airway area is by simple taping. This will give good results where the opening is of regular geometric shape such as a rectangle or circle. Airflow measuring stations should, wherever possible, be chosen where the airway profile is well defined. The frames of removed ventilation control doors can provide excellent sites for airflow measurement. Shapes such as arched profiles or trapeziums may be subdivided into simple rectangles, triangles and segments of a circle, and appropriate taped measurements taken to allow the area to be calculated.

Inevitably, there are many situations in which airflows must be determined in less well defined cross-sections. Several techniques are available for determining the corresponding cross-sectional area. For shapes that approximate to a rectangle, three or more heights and widths may be taped to find mean values of each. Care should be taken in such circumstances to make allowance for rounding at the corners. This often occurs due to spalled rock accumulating on the floor at the sides of airways.

A more sophisticated technique is the offset method in which strings are erected that define a regular shape within the airway. These strings are usually two vertical and two horizontal wires encompassing a rectangle. Taping from the wires to the rock walls at frequent intervals around the perimeter allows a plot of the airway profile to be constructed on graph paper.

The profilometer is a plane-table device. A vertical drawing board is attached to a tripod in the middle of the airway cross-section. Taped measurements made from the centre of the board to points around the rock walls may be scaled down mechanically or manually to reconstruct the airway profile on the drawing board. An electronic version replaces the tape by an ultrasonic distance measuring device although reflections of the beam can produce errors within the confines and rough surfaces of an underground airway.

The photographic method entails painting a white line around the perimeter of the measuring station. A linear scale such as a surveyor's levelling staff is fixed vertically within the defined
profile. A camera is located such that it is aligned along a longitudinal centre-line of the airway and with its lens equidistant from all points on the painted line. These precautions reduce perspective errors. The area within the white line may be determined by overlaying the resulting photograph with transparent graph paper.

Such time consuming methods tend to be employed for permanent measuring stations rather than for temporary survey stations. In all cases, the cross sectional area of conveyors, ducts or other equipment should be determined and subtracted from the overall area of the airway.

6.3. PRESSURE SURVEYS

The primary purpose of conducting pressure surveys is to determine the frictional pressure drop, \( p \), that corresponds to the airflow, \( Q \), measured in each branch of a survey route. There are essentially two methods. The more accurate is the gauge and tube or trailing hose method, in which the two end stations are connected by a length of pressure tubing and the frictional pressure drop measured directly. The second method, of which there are several variations, involves observing the absolute pressure on a barometer or altimeter at each station.

Although tradition within individual countries tends to favour one or other of the two methods, both have preferred fields of application. In general, where foot travel is relatively easy between measuring stations, the gauge and tube method can be employed. Where access is difficult as in multi-level workings or in shafts then the barometer method becomes more practicable.

6.3.1. Gauge and tube surveys

Figure 6.7 illustrates the principles of gauge and tube surveying. A pressure gauge is connected into a length of tubing whose other ends are attached to the total head tappings of pitot-static tubes sited at the end stations. In practice, of course, the tubing and instrumentation are all within the airway. Let us deal first with the essential theory of the method before discussing the practical procedure of gauge and tube surveying.

Theory

From the steady-flow energy equation (3.25) for an airway between stations 1 and 2, and containing no fan,

\[
\frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g = \int_{1}^{2} V dP + F_{12} \quad \text{J/kg} \quad (6.9)
\]

where

- \( u \) = air velocity (m/s)
- \( Z \) = height above mine datum (m)
- \( g \) = gravitational acceleration (m/s\(^2\))
- \( V \) = specific volume of air (= \( 1/\rho \)) (m\(^3\)/kg)

and \( F_{12} \) = work done against friction (J/kg)

If we assume a linear variation in air density between stations 1 and 2 then we can adopt an arithmetic mean value of density for the airway, \( \rho_a \). Furthermore, the frictional pressure drop referred to that density is given by equation (2.46) as

\[
\rho_{12} = \rho_a F_{12} \quad \text{Pa} \quad (6.10)
\]
Applying these conditions to equation (6.9) gives

\[
\rho_{12} = \rho_a F_{12} = \rho_a \left( \frac{u_1^2 - u_2^2}{2} \right) + \rho_a (Z_1 - Z_2)g - (P_2 - P_1) \quad \text{Pa} \quad (6.11)
\]

(See section 3.4.1 for a fuller explanation of this equation.)

However, velocity pressure

\[
p_v = \frac{\rho_a u^2}{2}
\]

and static pressure \( p_s = \rho_a Z g + P \) when referred to the mine datum for elevation.

Hence, equation (6.11) may be written as

\[
p_{12} = (p_{v1} + p_{s1}) - (p_{v2} + p_{s2}) = p_{t1} - p_{t2} \quad \text{Pa} \quad (6.12)
\]

where \( p_t \) = total pressure \( (p_v + p_a) \) as sensed by the total head tapping of a pitot-static tube.

This shows that the frictional pressure drop, \( p_{12} \), referred to the mean density in the airway between the pitot-static tubes is given simply as the pressure gauge reading shown as \( \Delta P \) in Figure 6.7. If that measured frictional drop is to be referred to a standard value of air density, \( \rho_{st} \), in order to compare or compound it with frictional pressure drops measured in other airways then the correction is given as
\[ p_{12} \text{ (standardized)} = p_{12} \frac{\rho_{st}}{\rho_a} \]

In the great majority of cases no further calculation is required. This explains why the gauge and tube technique is termed a direct method of measuring the frictional pressure drop in an airway. (But see Appendix A6 for situations where there is a significant difference in elevation between the two end stations)

**Practical Procedure**

The procedure for conducting a gauge and tube survey commences by assembling the equipment and calibrating the gauges. For convenience, a list of the required equipment is given here, together with some explanatory comments:

- 2 pitot-static tubes, approximately 1.25m in length. Shorter instruments may be employed for small airways or for use in ducts.

- An assortment of diaphragm pressure gauges ranging from a full scale deflection of not more than 100 Pa to the highest pressure developed by any fan in the system. The gauges should be calibrated in the horizontal position against a primary manometer immediately prior to an important survey. The use of diaphragm gauges rather than inclined manometers has greatly improved the speed of gauge and tube surveying.

- A continuous length of nylon or good quality plastic tubing between 100 and 200m in length. The tubing should be mechanically strong so that it can withstand being run over by rubber-tyred vehicles or being dragged under doors without permanent damage. An internal diameter from 2 to 3 mm is convenient. Larger tubing may become difficult to handle while the waiting time of transmission of a pressure wave may become unduly long if the tube is too narrow. The tube should be pressure tested before and after the survey.

- Short lengths of flexible tubing to connect the pitot-static tubes and gauge to the main tubing. Metal connectors and clamps should also be carried in case it becomes necessary to repair damage to the main tubing.

- 2 or 3 cans of spray paint for station marking. Chalk or industrial type crayons can also be used.

- 1 pocket barometer and 1 whirling hygrometer.

- 1 waterproof field book and pencils.

- 1 100m flexible measuring tape.

- Tool kit containing screwdrivers, adjustable spanners (wrenches) and a sharp knife.

The route of the traverse and sites of main junction stations should have been established before commencing the observations (Section 6.4). Two persons are required for a gauge and tube survey. It is helpful to have the lowest range gauge fixed within a box with a transparent top, and side holes for extended pressure tappings. Straps around the waist and neck of the observer hold the gauge in a horizontal position. This facilitates travelling and making observations for consecutive tube lengths along an airway.
The following procedure for making the observations is recommended:

1. At the starting station, the pressure tubing is unwound and laid out along the airway in the direction of the second main station. At the forward position, the zero setting of the gauge is checked and, if necessary, adjusted by connecting the high and low pressure tappings by a short length of tubing. The gauge is then connected in-line between the main tube and the total head tapping of the leading pitot-static tube as illustrated on Figure 6.7. At the rear position, the second pitot-static tube is similarly connected to the pressure tubing. The flexible tubing used for connections should be of an internal diameter that fits snugly on to the main tube, the gauge tappings and the pitot-static tube without requiring undue force.

2. To make the observation, both pitot-static tubes are held facing into the airflow, away from the body of the observer and at a position between one half and two thirds the height of the airway. The gauge is observed until the reading becomes constant. This may take two to three minutes depending upon the length and diameter of the main tube. Light tapping of the fingers may assist in overcoming any slight frictional resistance of the diaphragm or linkages within the gauge. On completing the gauge reading, the leading observer should indicate that fact to the trailing observer either by cap-lamp signals or by a tug on the tube. The barometric pressure, wet and dry bulb temperatures are also read and booked by the leading observer together with the distance between observers. In most cases this is the known length of the main tube. For shorter distances, the measuring tape or other means should be used to determine the actual length.

3. The final duty of the leading observer is to paint or chalk an indicator mark on the rail or airway side. A second tug on the tube or a cap-lamp signal indicates that it is time to move on. The leading observer walks forward, dragging the tube behind him. When the trailing observer reaches the indicator mark he simply stops, grasping the main tube firmly.

4. The procedure is repeated for each tube length until the next main (junction) station is reached.

The leading observer is kept busy while the trailing observer has little to do other than holding a pitot-static tube at each station or substation and walking forward. However, it is preferable that the observers exchange positions only in alternate shifts rather than during any one day. An experienced team can progress along a traverse route fairly quickly. Indeed, using modern equipment, it is usually the measurement of airflows by the accompanying airflow team rather than frictional pressure drops that dictates the overall speed of the survey (see section 6.4).

Each major junction of airways should be a main station within a gauge and tube traverse. At each of those junctions, the pitot-static tube should be held at the centre of the junction. If high turbulence causes excessive fluctuations on the gauge then the static tapping(s) on the pitot-static tube(s) may be employed. In this case, an anemometer should be held at the position of the pitot-static tube(s) to measure the local velocity. The corresponding velocity pressures should be calculated and applied as a correction to the gauge reading in order to determine the frictional drop in total pressure.

Care should be taken at all times to ensure that the pitot-static tubes do not become clogged by dust or other debris. Similarly, in wet conditions, it is vital to take precautions against water entering any tube. Pilot-static tubes or the open ends of pressure tubing should never be allowed to fall on to the floor during a traverse.

During the course of a pressure traverse, check readings should be taken of the pressure differences across doors between airways. It is convenient to carry a separate 10m length of flexible tubing for this purpose. It takes only a few seconds to attach a gauge of the required
range. If in doubt concerning the range, a high pressure gauge should be used first to establish
an approximate pressure difference, then exchanged for a more appropriate instrument if
necessary. It is usually sufficient to measure the static pressure across a door. Hence, the two
ends of the tubing should be protected against the very local air velocities that sometimes occur
from leakage close to a door. A practical way of doing this is simply to insert the end of the tube
into one’s pocket.

6.3.2. Barometer and altimeter surveys

If the absolute static pressures are measured on barometers at the two ends of a subsurface
airway then the difference between those two measured pressures will depend upon

- the difference in elevation between the stations,
- the air velocities, and
- the frictional pressure drop between the two stations at the prevailing airflow.

As the elevations and velocities can be measured independently, it follows that the barometric
readings can be used to determine the frictional pressure drop.

The concept of barometers was introduced in section 2.2.4.1. The instruments used for mine
barometric surveys are temperature compensated microaneroid devices. The facia of the
instruments are normally calibrated in kilopascals or other units of pressure. However, it will be
recalled that pressure may be quoted in terms of the column of air (or any other fluid) above the
point of measurement.

\[
P = \rho g h \quad \text{Pa} \quad \text{[see equation (2.8)]}
\]

If the air density, \( \rho \), and gravitational acceleration, \( g \), are regarded as constant then the pressure
may be quoted in head (metres) of air, \( h \). This relationship is utilized to inscribe the facia of some
aneroid barometers in terms of metres (or feet) of air column.

\[
h = \frac{P}{\rho g} \quad \text{m} \quad \text{(6.23)}
\]

The instrument then indicates an approximate elevation or altitude within the earth’s atmosphere
relative to some datum and, accordingly, is then called an altimeter. For a more accurate
elevation, the reading should be corrected for the difference between the actual values of \( \rho \) and
\( g \), and the standard values to which the altimeter has been calibrated. Some sophisticated
altimeters have an inbuilt bias which compensates for changes in air density with respect to
height. This allows a linear scale for altitude. For density compensated altimeters, the conversion
takes the form:

\[
\text{barometric pressure} = \exp(a - b \times \text{indicated altitude})
\]

where the constants \( a \) and \( b \) depend upon the units of pressure and altitude, and factory settings
of the altimeter.

In most mining countries, barometric pressure surveys are carried out using direct indicating
barometers. In the United States, altimeters are commonly employed. However, if the altimeter
readings are converted to pressure units then the two methods become identical.¹

¹ It would seem to have been the larger market (and, hence, reader availability) of altimeters together with
the concepts of a head of air and a head of water that led to the early use of altimeters in the United States.
Theory

Again, we commence with the steady flow energy equation for an airway between stations 1 and 2, and containing no fan. In the usual case of polytropic flow, the energy equation gives the work done against friction as:

\[
F_{12} = \frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g - R(T_2 - T_1)\ln\left(\frac{P_2}{P_1}\right) \quad \text{J} \quad \text{kg}^{-1} \quad (6.24)
\]

(see equation (8.1))

or, for isothermal flow where \(T_1 = T_2\)

\[
F_{12} = \frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g - RT_1\ln\left(\frac{P_2}{P_1}\right) \quad \text{J} \quad \text{kg}^{-1}
\]

where

\[
\begin{align*}
P & = \text{barometric pressure (kPa)} \\
T & = \text{absolute temperature (degrees Kelvin)} \\
Z & = \text{elevation of barometer location (m)} \\
u & = \text{air velocity \textit{at the barometer} (m/s)} \\
R & = \text{mean gas constant (J/kg K) [from equation (14.14)]}
\end{align*}
\]

As all parameters are measurable in these relationships, the work done against friction, \(F_{12}\) can be determined. This, in turn, can be converted into a frictional pressure drop, \(p_{12}\), referred to any given air density, \(\rho_a\).

\[
p_{12} = \rho_a F_{12} \quad \text{Pa} \quad \text{[see, also, equation (6.10)]}
\]

A complication arises if the barometric pressures at the two stations are not read simultaneously. In this case, the surface atmospheric pressure may change during any time interval that occurs between readings at successive stations. If the atmospheric pressure at a fixed control station is observed to increase by \(\Delta P_c\) during the time elapsed while moving from station 1 to station 2, then the initial value, \(P_1\), should be corrected to

\[
P_1 + \Delta P_c \quad (6.25)
\]

The correction, \(\Delta P_c\), may, of course, be positive or negative. By assuming a series of polytropic processes connecting the control barometer (subscript c) to the traverse barometer (subscript 1), it can be shown that a more accurate value of the correction is given as

\[
\Delta P_c = \frac{P_1}{P_c} \quad (6.26)
\]
Example
The following two lines are an excerpt from a barometer field book.

<table>
<thead>
<tr>
<th>Station No.</th>
<th>Time</th>
<th>Traverse barometer ( P ) kPa</th>
<th>Temperatures ( t_d ) °C</th>
<th>Temperatures ( t_w ) °C</th>
<th>Elevation ( Z ) m</th>
<th>Velocity ( u ) m/s</th>
<th>Control barometer ( P_c ) kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13:42</td>
<td>103.75</td>
<td>15.6</td>
<td>13.0</td>
<td>2652</td>
<td>2.03</td>
<td>98.782</td>
</tr>
<tr>
<td>2</td>
<td>14:05</td>
<td>104.61</td>
<td>17.2</td>
<td>14.2</td>
<td>2573</td>
<td>1.52</td>
<td>98.800</td>
</tr>
</tbody>
</table>

Using the psychrometric equations given in section 14.6, the moisture contents of the air at stations 1 and 2 were calculated to be

\[ X_1 = 0.008035 \text{ kg/kg dry air} \]

and

\[ X_2 = 0.008536 \text{ kg/kg dry air} \]

Equation (14.14) then indicates the corresponding gas constants as

\[ R = \frac{287.04 + 461.5 X}{1 + X} \]

giving \( R_1 = 288.431 \text{ J/kg °C} \) and \( R_2 = 288.517 \text{ J/kg °C} \) with an arithmetic mean of 288.474 J/kg °C.

During the time period between taking barometer readings \( P_1 \) and \( P_2 \) the control barometer registered an increase in atmospheric pressure of

\[ \Delta P_c = 98.800 - 98.782 = 0.018 \text{ kPa} \]

Equation (6.26) gives the corrected reading at station 1 as

\[ P_1 + \Delta P_c \frac{P_1}{P_c} = 103.75 + 0.018 \times \frac{103.75}{98.782} \]

\[ = 103.75 + 0.019 = 103.769 \text{ kPa} \]

The steady flow energy equation (equation (6.24) then gives

\[ F_{12} = \frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g - R(T_2 - T_1) \ln\left(\frac{P_2}{P_1}\right) \ln\left(\frac{T_2}{T_1}\right) \quad \text{J/kg} \]

where

\[ T_1 = 273.15 + 15.6 = 288.75 \text{ K} \]

and

\[ T_2 = 273.15 + 17.2 = 290.35 \text{ K} \]
\[ F_{12} = \frac{2.03^2 - 1.52^2}{2} + (2652 - 2573)9.81 - 288.474(17.2 - 15.6) \ln\left(\frac{104.61}{103.769}\right) \ln\left(\frac{290.35}{288.75}\right) \] \[ \frac{J}{kg} \]

\[ = 0.91 + 774.99 - 674.22 \] \[ \frac{J}{kg} \]

\[ = 101.7 \] \[ \frac{J}{kg} \]

and the frictional pressure drop referred to standard density becomes

\[ \rho_{12} = F_{12} \rho = 101.7 \times 1.2 \]

\[ = 122 \] \[ Pa \]

(See, also, sections 8.2.2. and 8.3.3. for further examples.)

**Practical Procedure**

A barometric survey can be conducted with one observer at each station although an additional person at the traverse stations facilitates more rapid progress. The equipment required is as follows:

- 2 microaneroid barometers (or altimeters) of equal precision
- 1 whirling or aspirated psychrometer
- 2 accurate watches
- 1 anemometer
- 1 2m measuring tape
- waterproof field books and pencils
- 2 or 3 cans of spray paint to mark station numbers.

The microaneroids should be calibrated against a primary barometer prior to an important survey. A calibration cabinet can be constructed with the internal pressure controlled by compressed air feeds and outlet valves. In addition to pressure calibration, the instruments should be checked for temperature compensation and creep characteristics. Modern instruments are stable over the range of temperatures normally encountered in mines and adapt to a change in pressure within a few minutes.

For an underground barometer traverse only the main junctions need be considered as measurement stations. Intermediate substations, as required in the gauge and tube technique, are normally unnecessary. However, for main ventilating shafts, the most accurate results are obtained by taking readings at intervals down the shaft (Section 8.2.2).

There are essentially two methods of handling the natural variations in atmospheric pressure that occur during the course of the survey. One technique is to maintain a barometer at a fixed control station and to record or log the readings at intervals of about 5 minutes. The second method is the leapfrog procedure in which both barometers are used to take simultaneous readings at successive stations. After each set of readings, the trailing barometer is brought up to the forward station where the two barometers are checked against each other and reset if necessary. The trailing barometer is then moved on to assume the leading position at the next station.
Chapter 6. Ventilation Surveys

The traverse procedure commences with the observers synchronizing their watches. If the control station method is used, the control should be established in a location that is reasonably stable with respect to temperature and not subject to pressure fluctuations from fans, ventilation controls, hoists or other moving equipment. A location on surface near the top of a downcast shaft and shaded from direct sunlight is usually satisfactory. A recording barometer may be employed at the control station, but only if it provides a precision equivalent to that of the traverse barometer.

At each traverse station the following readings are logged:

- date, barometer identification and name of observer
- number and location of station
- time
- barometer reading
- wet and dry bulb temperatures
- anemometer reading at the position of the traverse barometer.

The location of each station should be correlated with surveyors’ plans to determine the corresponding elevation. The traverse barometer should be held at the same height above the floor at each station in order that its elevation can be ascertained to within 0.5m.

The anemometer should be employed to measure the air velocity at the position of the barometer. There is no need to conduct an anemometer traverse. As shown in the example given in the previous subsection, the effect of air velocity is usually small compared with the other terms in the steady-flow energy equation.

6.4 ORGANIZATION OF PRESSURE-VOLUME SURVEYS

The preceding two sections have discussed the techniques of measuring volume flows, \( Q \), and frictional pressure drops, \( p \), separately. It will be recalled that the results of the two types of survey will be combined to give the resistance, \( R = p/Q^2 \), and airpower loss, \( pQ \), of each branch. As airflows and, hence, frictional pressure drops vary with time in an operating subsurface facility, it follows that \( p \) and \( Q \) should, ideally, be measured simultaneously in any given airway. Typically, there are two observers measuring airflows and another two involved in the pressure survey. The two teams must liaise closely.

6.4.1. Initial planning

A pressure-volume survey should be well planned and managed. The practical work for a major survey commences a week or two before the underground observations by assembling, checking and calibrating the equipment. In particular, it is inadvisable to rely upon manufacturers’ original calibrations of vane anemometers or diaphragm pressure gauges. If the equipment required for calibration is unavailable locally then the work may be carried out by a service organization or the instruments returned to the manufacturers for customized calibration. The calibration is normally produced as a table of corrections against indicated readings and taped to the side of the instrument or carrying case. Interpolation from the table can be carried out at the time of measurement so that the reading, correction and corrected observation can all be logged immediately.

The mine plan should be studied carefully and the routes of the survey selected. A full mine survey will include each ventilation connection to surface and the infrastructure of airways that comprise the primary ventilation routes. Subsidiary survey routes may be appended to include individual working districts or to extend a data bank that exists from previous surveys. The routes should be chosen such that they can be formulated into closed traverse paths or loops within the ventilation network of the mine. Branches that connect to the surface close through the pressure...
sink of the surface atmosphere. A main loop in a large mine may take several days to survey. However, each main loop should be divided into smaller subsidiary loops each of which can be closed within a single day of surveying.

An initial reconnaissance of the mine should be carried out, travelling through all airways selected for the primary traverses and establishing the locations of main stations. These are normally at major junctions of the ventilation system. Where two or more airways are adjacent and in parallel - and the gauge and tube method is employed for the pressure measurements - then it is necessary to take those measurements in one of the airways only. However, to obtain the total airflow in that composite branch of the network, it will be necessary to take flow measurements at corresponding points in each of the parallel airways. Airflow measuring stations should be selected and marked on the plan and, also, on the walls of the airway.

The subsequent employment of survey data for ventilation network analysis and forward planning (Chapters 7 and 9) should be kept in mind during the management of ventilation surveys. The identification number assigned to each network junction should give an indication of the location of the junction within the mine. In multi-level workings, for example, the first integer of station numbers may be used to indicate the level.

A pre-survey briefing meeting should be held with all observers present. Each observer should be fully trained in survey procedures, use of the instruments and techniques of observation. The traverse routes and system of station identification should be discussed, together with an outline schedule covering the days or weeks required to complete the survey.

6.4.2. Survey management

During production shifts, the airflows and pressure drops in an underground mine are subject to considerable variation due to movement of equipment, changes in resistance in the workings and opening of ventilation doors. Hence, the best time for ventilation surveys is when the mine is relatively quiescent with few people underground. During the duration of a survey, the observers should be prepared to work at weekends and on night shifts.

Although the frictional pressure drop and corresponding airflow should, ideally, be measured simultaneously in each leg of the traverse, this is often not practicable. Nevertheless, the teams should stay fairly near to each other so that there is a minimum delay between the two sets of measurements in a given branch. With experienced observers the teams maintain close liaison, assisting one another and always being conscious of the activity of the other team. This avoids the infuriating situation of the pressure team opening doors to take a check reading while the airflow team is in the middle of an anemometer traverse. Friendships have been known to suffer on such occasions.

Immediately following each shift the two teams should check all calculations carried out underground, transcribe the results of that shift's work from the field books to clean log sheets and, also, to a large scale copy of a mine map. Positions of measured airflows and pressure drops should be reviewed by both teams to ensure compatibility of measurement locations and to correlate identification of station numbers. Any difficulties encountered during the shift should be discussed. The final half hour or so of each working day may be spent in reviewing the ground to be covered in the following shift and the allocation of individual duties.

6.4.3. Quality assurance

It is most important that control is maintained over the quality of all aspects of an important ventilation survey, from initial calibration of the instruments through to the production of final results. Field books or booking sheets should be laid out clearly such that persons other than the observers can follow the recording of observations and calculations carried out underground. All calculations should be checked by someone other than the originator. Most of the calculations
involved in ventilation surveys are quite simple and may be carried out on a pocket calculator. The exception is for barometric surveys where a verified program for a personal computer is very helpful. Commercially available spreadsheet software can readily be adapted for this purpose.

Adherence to Kirchhoff's Laws should be checked both at the time of observations wherever practicable and, also, during the data transposition at the end of each shift. These laws are discussed fully in Chapter 7. Briefly, Kirchhoff I requires that the algebraic sum of airflows entering any junction is zero. Kirchhoff II states that the algebraic sum of standardized pressure drops around any closed loop must also be zero, having taken fans and natural ventilation pressures into account. In a level or near level circuit, the closing error of a pressure loop may be expressed as the actual closure divided by the sum of the absolute values of the measured frictional pressure drops around the loop. This should not exceed 5 per cent. The check measurements of pressure differentials across doors are invaluable in tracing or distributing observational errors. In the case of loops involving significant changes in elevation such as shaft circuits, the sum of standardized pressure drops will be a combination of observational errors and natural ventilating effects. The latter may be determined independently from temperature and pressure measurements as discussed in section 8.3.

It is vital that good records be kept of each phase of a survey. The survey team leader should maintain a detailed journal of the activities and achievements of each working day. This should include the clean log sheets of results transcribed from the field books at the end of each shift.

The conclusion of a major survey should see the establishment of a spreadsheet type of data bank or the extension of an existing data bank, holding the frictional pressure drop and corresponding airflow for every branch included in the survey. Other details such as the dates of observations, names of observers, instrument identifications and dimensions of airways may be included. The data bank may then be used to calculate airway resistances, airpower losses and friction factors, and also provides a data base from which a computer model of the mine ventilation network can be generated (Chapter 9). Additionally, the resistances, resistance per unit length and airpower losses may be shown on a colour-coded map in order to highlight sections of airways that are particularly expensive to ventilate.

6.5. AIR QUALITY SURVEYS

While pressure-volume surveys are concerned with the distribution of airflow around a ventilation system, the subsurface environmental engineer must also maintain control of the quality of that air, i.e. the concentrations of gaseous or particulate pollutants, and the temperature and humidity of the air. Such measurements should be made at specified times and places to ensure compliance with mandatory standards and with a regard for the safety and health of the workforce.

Details of the techniques of measuring and quantifying levels of dust, gas concentrations and climatic conditions are given in Chapter 23, 11 and 14 respectively. In addition to mandatory measurements a set of such observations made in a systematic manner around a continuous path is known as an air quality survey. This procedure should be employed for two reasons. First, it provides a means of tracking and quantifying the variation in pollutant levels and, secondly, it enables zones of emission of gases, dust, heat and humidity to be identified. Measurements of gas concentration are often made as a normal part of a pressure-volume survey in a gassy mine. Similarly the observations of barometric pressure, wet and dry bulb temperature made during a pressure survey may be used to compute and plot the variations in psychrometric conditions throughout the traverse paths.
BIBLIOGRAPHY


Appendix A6.

Application of the gauge and tube method of measuring frictional pressure drops in cases of significant differences in elevation.

To this time, the gauge and tube technique has seldom been used for vertical shafts or highly inclined airways although the often difficult task of measuring shaft resistance would be greatly facilitated by leaving a length of small bore pressure tubing permanently in the shaft. Where the ends of the tube are at significantly different elevations a complication does, however, arise. It is found that in these circumstances, the reading depends upon the location of the gauge and increases as the elevation of the gauge decreases within the airway. This phenomenon occurs because the air within the tubing is stationary and, hence, not affected by friction. The pressure at all points within the tube differs from that outside the tube at the same elevation. For example, if the gauge is located at the bottom of a downcast shaft, as shown in Figure A6.1 the pressure in the tube will be higher than at a corresponding elevation outside the tube. If the temperature and moisture content inside and outside the tube are the same at corresponding points it follows that the mean density in the tube must be a little higher than that in the airway.

If the gauge is to indicate directly the frictional pressure drop referred to the mean density in the airway, \( \rho_a \), then it must be located at the position of mean density. In shafts or other airways of constant slope and resistance, this is very close to the midpoint. However, it is usually difficult to take measurements at this position and it is more practicable to site the pressure gauge either at the top or bottom of the shaft. A correction must then be applied to the reading in order to arrive at the frictional pressure drop referred to the mean air density.

We shall continue this analysis assuming the gauge to be at the base of a downcast shaft (Figure A6.1). The pressure in the tubing at the high pressure tapping is \( P_c \) and that at the low pressure tapping is \( P_b \). The gauge reads \( \Delta P = P_c - P_b \). However, the pressure \( P_c \) must equal the total pressure at station 1 plus the pressure due to the head of static air within the tube

\[
P_c = P_1 + \frac{\rho_1 u_1^2}{2} + \Delta Z g \rho_t
\]

where \( P \) = barometric (static) pressure
\( u \) = air velocity
\( \Delta Z \) = depth of shaft
and \( \rho_t \) = mean air density within the tube

And, at the low pressure tapping of the gauge

\[
P_b = P_2 + \frac{\rho_2 u_2^2}{2}
\]

Figure A6.1  Gauge at the bottom of a downcast shaft. The gauge is depicted as a manometer to show the direction of the pressure difference.

\(^2\) Where such a tube is left in place permanently, it should be tested for leaks and internal condensate before being used for a frictional pressure drop observation. A disconnected compressed air pipe may be used as a temporary pressure tube.
Then
\[ \Delta P = P_c - P_b = \frac{\rho_1 u_1^2 - \rho_2 u_2^2}{2} + \Delta Z g \rho_1 + (P_1 - P_2) \] (6.13)

Now, from equation (6.11), the frictional pressure drop in the airway, referred to the airway mean density, \( \rho_a \), is given as
\[ \rho_{12} = \rho_a \frac{u_1^2 - u_2^2}{2} + \Delta Z g \rho_a + (P_1 - P_2) \] (6.14)

Hence, the "error" in the gauge reading becomes
\[ \varepsilon = \Delta P - \rho_{12} = \left[ \frac{\rho_1 u_1^2 - \rho_2 u_2^2}{2} - \left( \frac{u_1^2 - u_2^2}{2} \right) \rho_a \right] + \Delta Z g (\rho_1 - \rho_a) \] (6.15)

We can substitute for
\[ \rho_a = \frac{\rho_1 + \rho_2}{2} \] (Mean density in airway)
\[ \rho_t = \frac{\rho_1 + \rho_c}{2} \] (Mean density in tube)

where \( \rho_c = \) density in tube at position c.

Now \[ \rho_c = \frac{P_c}{RT_2} \quad \text{and} \quad \rho_2 = \frac{P_2}{RT_2} \]
giving \[ \rho_c - \rho_2 = \frac{P_c - P_2}{RT_2} = \frac{\Delta P \rho_2}{P_2} \] (ignoring the small effect of velocity pressure on the air density at position b.)
or \[ \rho_c = \rho_2 + \frac{\Delta P}{P_2} \rho_2 \]

Then, after some algebraic simplification, equation (6.15) becomes
\[ \varepsilon = \frac{\Delta Z g \Delta P \rho_2}{2P_2} - \frac{(u_1^2 + u_2^2)}{4} (\rho_2 - \rho_1) \] (6.16)

giving
\[ \rho_{12} = \Delta P - \varepsilon = \Delta P \left[ 1 - \frac{\Delta Z g \rho_2}{2P_2} \right] + \frac{(u_1^2 + u_2^2)}{4} (\rho_2 - \rho_1) \] (6.17)

This is the full form of the equation that allows the reading on the gauge at the base of the shaft or slope to be corrected to mean density for the airway.
The term \( \frac{\Delta Z g \rho_2}{2P_2} \)

arises from the difference in mean air density between the airway and the tubing (equation (6.15),

while \( \frac{(u_1^2 + u_2^2)}{4} (\rho_2 - \rho_1) \)

is the result of converting the velocity pressures at \( \rho_1 \) and \( \rho_2 \) to the mean density \( \rho_a \). To be precise, this latter term should be applied even when the airway is level. However, it is normally insignificant and may be ignored for practical purposes, giving the frictional pressure drop referred to the mean air density in the shaft as

\[
p_{12} = \Delta P \left(1 - \frac{\Delta Z g \rho_2}{2P_2}\right)
\]

Equation (6.18) illustrates that the uncorrected reading, \( \Delta P \), on the shaft bottom gauge overestimates the actual frictional pressure drop.

Similar reasoning leads to the following equations for other configurations:

**Gauge at the top of a downcast shaft**

\[
p_{12} = \Delta P_{\text{top}} \left(1 + \frac{\Delta Z g \rho_1}{2P_1}\right) + \frac{(u_1^2 + u_2^2)}{4} (\rho_2 - \rho_1)
\]

**Gauge at the base of an upcast shaft**

\[
p_{34} = \Delta P_{\text{top}} \left(1 - \frac{\Delta Z g \rho_3}{2P_3}\right) + \frac{(u_3^2 + u_4^2)}{4} (\rho_3 - \rho_4)
\]

(Subscripts 3 and 4 refer to the bottom and top respectively of an upcast shaft.)

**Gauge at the top of an upcast shaft**

\[
p_{34} = \Delta P_{\text{top}} \left(1 + \frac{\Delta Z g \rho_4}{2P_4}\right) + \frac{(u_3^2 + u_4^2)}{4} (\rho_3 - \rho_4)
\]

Again, the kinetic energy term involving \( u \) values can usually be neglected.

Hinsley, in 1962 showed that for both downcast and upcast shafts the frictional pressure drops are given to a good approximation by the arithmetic average of the gauge readings at the top and bottom of the shaft.
Calculated Example

The following data\(^3\) were established for a downcast shaft fitted with a tube throughout its length. A pressure gauge can be connected to either the top or the bottom of the tube. Ignoring the small effects of air velocity, determine the frictional pressure drop, \(p_{12}\), referred to the mean air density in the shaft.

Depth of shaft = 1219.2 m

<table>
<thead>
<tr>
<th></th>
<th>Top of shaft</th>
<th>Bottom of shaft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barometric pressure, kPa</td>
<td>101.591</td>
<td>117.015</td>
</tr>
<tr>
<td>Air density, kg/m(^3)</td>
<td>1.275</td>
<td>1.408</td>
</tr>
<tr>
<td>(from psychrometric measurements – ref. Chapter 14, Section 6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure gauge when</td>
<td></td>
<td></td>
</tr>
<tr>
<td>connected to top of tube, Pa</td>
<td>566</td>
<td></td>
</tr>
<tr>
<td>Pressure gauge when</td>
<td></td>
<td></td>
</tr>
<tr>
<td>connected to base of tube, Pa</td>
<td>655</td>
<td></td>
</tr>
</tbody>
</table>

Solution

(a) Using the pressure gauge reading at the top of the shaft, equation (6.19) applies. Ignoring the kinetic energy terms:

\[
p_{12} = \Delta P\text{(top)} \left\{ 1 + \frac{\Delta Z g \rho_1}{2P_1} \right\}
\]

\[
= 566 \left\{ 1 + \frac{1219.2 \times 9.8066 \times 1.275}{2 \times 101591} \right\} = 608 \text{ Pa}
\]

(b) Using the pressure gauge reading at the bottom of the shaft equation (6.18) applies.

\[
p_{12} = \Delta P \left\{ 1 - \frac{\Delta Z g \rho_2}{2P_2} \right\}
\]

\[
= 655 \left\{ 1 - \frac{1219.2 \times 9.8066 \times 1.408}{2 \times 117015} \right\} = 608 \text{ Pa}
\]

In both cases, \(p_{12}\) is referred to the mean air density in the shaft and, hence, give the same result. (In practice, it is to be expected that there will not be exact agreement between the results of shaft top and shaft bottom gauge locations because of observational errors.)

---

\(^3\) The given data are taken from Hinsley, F.B. (1962) on the basis of a frictional adiabatic process in a dry shaft. [“The Assessment of Energy and Pressure Losses due to Airflow in Shafts, Airways and Mine Circuits” (Section IV). The Mining Engineer, Vol.121, No. 23, August 1962.]
The arithmetic mean density in the shaft is

\[
\rho_{\text{mean}} = \frac{1.408 + 1.275}{2} = 1.341 \text{ kg/m}^3
\]

If corrected to standard air density \(\rho_{\text{st}} = 1.2 \text{ kg/m}^3\) for comparison with other airways, the standardized frictional pressure drop becomes

\[
\rho_{\text{st}} = \rho_{12} \times \frac{\rho_{\text{st}}}{\rho_{\text{mean}}} = 608 \times \frac{1.2}{1.341} = 544 \text{ Pa}
\]

To check the approximate method of establishing the frictional pressure drop from the mean of the top and bottom gauge readings:

The arithmetic mean of the pressure gauge readings at the top and bottom of the shaft is

\[
\frac{566 + 655}{2} = 610.5 \text{ Pa}
\]

showing that, in this case, the approximation is in excellent agreement with the calculated 608 Pa.