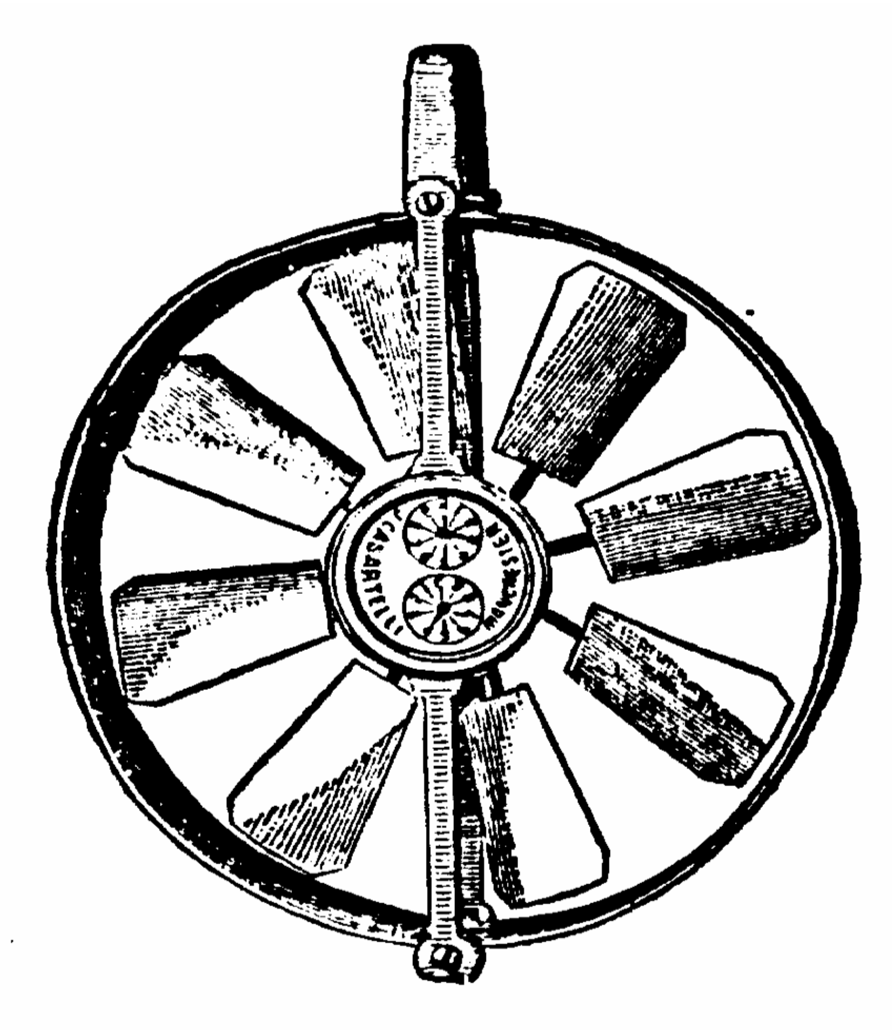
The Measurement of Air Flow in British Coal Mines: A Historical Review



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CONTENTS

LIST OF DIAGRAMS

PREFACE

Many papers, for example Hinsley (1), Mining Association of Great Britain (2) and Saxton (3), have been written on the subject of mine ventilation history. Middleton (4) has produced a comprehensive study of the history of meteorological instruments and Medlock (5) has written a historical review of flow metering. A literature survey did not, however, locate any studies of the air flow measurement practices and apparatus applied within the coal mining industry. In view of the extensive use of anemometers underground and the advances in air flow measurement technology this has fuelled, it was decided to rectify this omission.

The results to the study of the history of coal mine air flow measurement practices and instruments were first presented to Nottingham University in 1988 in a thesis for the award of the degree of Master of Philosophy. However, in producing the following redraft the aim has been to try and make the monograph of interest to readers outside the coal mining industry, as well as those within it.

Part 1 of this study reviews the development of air flow measurement practices in coal mines, whilst Part 2 describes the historical development of the apparatus used. Throughout the monograph the subjects are treated from a practical point of view, with discussion of the theory behind an instrument's operation kept to a minimum. Brief outlines of the research and development organisation within the nationalised British coal industry and the use of electrical equipment underground are included as Appendices.

Thanks are also due a large number of now ex-British Coal staff who gave their help and support. During the research covered by this study many individuals and organisations outside the mining industry were contacted. Many provided valuable information. Their help is gratefully acknowledged. The author would also like to thank his family for providing the motivation to complete this work.

In many places results obtained by employees of the National Coal Board, the British Coal Corporation and its contractors are discussed. The views expressed on these and any other subjects within the monograph are those of the author.

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Chapter 1 Environmental control in coal mines

As recorded by Agricola (1), Pliny (AD 23 to 79) describes how, in Roman times, gases dangerous to humans sometimes occurred in pits and wells. He also describes how they were detected by observing the behaviour of a dog or lighted candle when lowered down the shaft. They were removed by passing a current of fresh air through the workings.

In British coal mines one such dangerous gas, almost certainly being encountered by the fourteenth century, was called ‘blackdamp’ or ‘chokedamp’. This was probably in response to the fact that its presence was indicated by naked flames being extinguished and humans suffocating. Blackdamp is now recognised as occurring due to the presence underground of oxidising processes, including breathing humans, burning candles and the spontaneous combustion of coal. Thus it would have been particularly prevalent in workings not scoured by a current of fresh air drawn in from the surface. Typically these would have been the single entry ‘bell pits’. Other early mines were formed with two or more access points, or shafts. When these were at different elevations it was found that seasonal differences between the surface air and ground temperatures generated a pressure drop between the ‘pit bottoms’. This caused a current of air to spontaneously flow through any interconnecting workings. Although weak and unreliable, this ‘natural’ ventilation would have helped remove any blackdamp created during normal mining operations.

During the seventeenth century another gaseous hazard began to appear in coal mines. Rather than snuffing out flames, the presence of so called ‘firedamp’ caused them to burn more vigorously. Further, it was found that if the lamp was not extinguished, or a current of air passed through the affected work places, a devastating explosion could occur.

One of the earliest deaths attributed to an explosion of firedamp occurred in 1621 (2). Unfortunately, it was not to be the last and although no formal accident statistics were being collected at this time, it is clear that the number and severity of such incidents rose subsequently. An identified cause was an increase in the demand for coal and, consequentially, the depth and size of mines; coal bearing strata becomes more ‘gassy’ with depth and the ventilation current generated by a given pressure difference weaker the longer the path it has to traverse.

Faced with the problem of firedamp some owners chose to ignore it. Others took a more proactive approach, voluntarily instigating measures to try and prevent its ignition. One explosion prevention measure applied in pre-nineteenth century coal mines involved passing a single current of air through all the open workings in sequence. The application of this approach seems to have been based on the idea that the critical variable in the removal of the noxious gases was the air speed. Although no supporting evidence has been located, it is speculated that primitive flow detection techniques may have been in use by this time to test whether all the workings had moving air in them. These would have included observing the cooling sensation on the human skin (see Chapter 12) and the movement of light ‘tracer’ objects, such as dandelion seeds and smoke, suspended on the current (see Chapter 6).

Initially, the pressure drops required to ventilate mines were generated by natural means. However, as workings became more extensive, the application of this approach became incapable of preventing the occurrence of an increasing number of devastating explosions. This is evident from the graphic descriptions of such events published from the seventeenth century onwards. In an attempt to generate greater pressures, baskets of burning coal were hung in one of the shafts. This enhanced the heating power of the strata relative to that of the surface air. By the middle of the nineteenth century large furnaces were being constructed at the bottom of what was being called the ‘upcast’ shaft. The other shaft became known as the ‘downcast’. Underground, this was connected to the ‘intake’ airway. The ‘foul’ air was returned to the upcast shaft along the ‘return’.

By the 1840’s, a recognition of the importance of ensuring that the mine’s ventilator was always generating a flow perceived as being adequate to disperse any firedamp released into the workings had led to the application of crude air flow sensors at such locations. Typically these consisted of a piece of wood suspended from a string. When exposed to a flow they were deflected from the vertical. The furnace attendant was required to add sufficient coals to keep this constant. Another instrument applied to mine ventilation at around this time was the water filled 'U' tube manometer, or 'water gauge'. This showed the ventilating pressure being developed between the intake and return airways.

Although fires and furnaces proved capable of generating more reliable and higher air flows than the natural methods, it was recognised that they could represent a significant explosion hazard in the presence of firedamp collected from the workings. A search for safer alternatives eventually led to the application of surface mounted fans. The first was used with any success at a British coal mine 1827. These early devices were driven by steam engines and considerable debate subsequently ensued as to their relative merits, particularly in respect of their operating efficiencies, over the established techniques. The methodologies and apparatus that were developed to test the performance of ventilators from about this period on are described in Chapter 5.

All large modern mines are ventilated by surface mounted high speed electric fans. During the latter half of the twentieth century such installations began to be fitted with sophisticated computer based monitoring systems covering a range of ventilator operating parameters. These included the pressure between the upcast and downcast shafts and the mechanical state of the machinery. By observing and analysing trends in such variables it has been found possible to identify developing system problems and avoid catastrophic ventilation failure through advanced maintenance.

Smaller fan units are used underground to provide local enhancement of the flow. The air flow measurement and monitoring techniques applied to these so called 'auxiliary' ventilation systems are described in Chapter 4.

As noted above, before the nineteenth century, the ventilating current of a coal mine was directed through all the working places in succession. By the turn of the nineteenth century, collieries were becoming very large. As an example, by 1812 Killingworth, near Newcastle-upon-Tyne, had 256 km of workings. With such path lengths it was found that even with the application of the best available ventilation practices explosions still occurred. This was because the pressures available were unable to force sufficiently high quantities of fresh air underground to ensure the safe dilution of the firedamp released during normal mining operations.

An attempt at solving this problem was made in about 1810 when John Buddle, the manager of Wallsend Colliery on the River Tyne, introduced a new method of ventilation. In this, the mine was divided into a number of separate 'districts'. Each was supplied by fresh air split from a main intake. The foul air was discharged into a common return. The application of this system resulted in mine ventilation networks formed from a number of relatively short air paths joined in parallel. It can be shown that this enabled a given mine pressure difference to generate a much higher total quantity flow of fresh air than had hitherto been possible.

Modern coal mine ventilation is based upon Buddle's system, although there are fewer districts and splits in the intake air current.

By the early nineteenth century it had become known that firedamp became explosive when the flammable gas concentration was between approximately 5 and 15% by volume. The fact that Buddle's ventilation system maximised the quantity of fresh air flowing through the mine rather than necessarily its speed demonstrates a recognition of the significance of this variable in the rendering of noxious gases safe. Coupling this with the fact that it was important that the intake was balanced between a number of parallel systems, possibly formed from roadways with differing cross sectional areas, meant that new air flow measuring methods were required. Rather than indicate speed, they had to provide accurate indications of the quantity flowing. The methodologies that have been developed to fulfil this requirement are described in Chapter 2.

On 25 May 1812 an explosion occurred at Felling Colliery, near Gateshead-on-Tyne, killing ninety-two men and boys. Reports of the circumstances behind this accident had such an impact on a London barrister called Mr Wilkinson that he published proposals for the formation of a society to consider ways of preventing such incidents. Called the 'Sunderland Society' its first meeting was held on 1 October 1813. The main result of their deliberations was the invention by Sir Humphrey Davy, working under their auspices, of his now famous flame safety lamp. Basically, this consisted of an enclosure for a naked flame such that, in theory, it was incapable of igniting any explosive concentrations of gas that may be present in its surroundings. It was produced in 1816. At almost exactly the same time George Stephenson devised a similar safety lamp.

Despite the introduction of flame safety lamps into coal mines, explosions of firedamp remained a significant problem. Although no formal accident statistics were collected at the time, the number occurring seemingly continued along a rising trend that had been apparent before the Sunderland Society began its deliberations. Responding to this, in 1834 a petition was introduced before Parliament requesting that action be taken to do something about the situation. In response the House of Commons set up a Select Committee to study the occurrence of accidents in coal mines. The report (3) made no recommendations as to how they could be avoided with certainty, although they did reiterate the then well known fact that one of the best methods was to ensure that an adequate supply of air reached all parts of the mine.

Over the next four years it is probable that over three hundred coal miners died in explosions. Despite this, still no official action was taken in an attempt to prevent such from occurring.

In June 1839 fifty-two men and boys were killed in an explosion at St Hilda Colliery, County Durham. A member of the local community, James Mather, was so moved that he suggested that a committee be formed to study the prevention of accidents in coal mines. The group was called the 'South Shields Committee'. As a review of coal mining practices and safety, the report subsequently produced (4) must be seen as a classic. In a similar vein to the 1835 Select Committee, it concluded that: 'Ventilation seems to be the only certain and secure means of safety in inflammable mines..... Whilst this imperfect ventilation is allowed to continue, the mining districts and the public must prepare themselves for the continual recurrence of these dreadful calamities (explosions).'

Unlike any of the earlier reports into coal mine accidents, that of the South Shields Committee included a detailed discussion of how scientific instruments could be used to improve safety. The uses of barometers, thermometers and anemometers were all strongly recommended. Readings of the barometer could provide warning of higher than normal emission levels of flammable and other pollutant gases, thereby showing when to increase the air flow through the workings. This could be achieved by increasing the air temperature difference between the upcast and downcast shafts, as indicated by thermometers. Anemometers could then be used to ensure that all parts of a mine were receiving their appropriate share of the intake supply.

According to Galloway (2), up to the 1830's the larger coal mining accidents occurred primarily around Newcastle upon Tyne and Durham. After this they became more widespread. This 'encouraged' the Government to begin taking a greater interest in coal mine safety than hitherto. Ignoring any debate over the validity of this statement, from 1845 onwards numerous official investigations were commissioned into the subject of accidents in coal mines. These revealed that whilst the safety standards applied in the North East of England were the best possible given the level of knowledge available, in other areas they were not. Further, many operators were unwilling to make any improvements. Consequently it became apparent that legislation governing underground operations was necessary if there was any hope of getting majority acceptance of 'best mining practice', particularly from a safety point of view.

The first Coal Mines Act was passed in 1850. This created a Mines Inspectorate with the power to enter any workings and advise the manager of any dangerous conditions found therein. It also required that all fatal accidents be reported to the Home Office within twenty-four hours of occurring. For the first time, this allowed an accurate assessment to be made of the causes of death amongst coal miners.

In 1853 the Government set up another Select Committee to investigate accidents in mines. This reported in 1854. Using statistics collected under the 1850 Act it was shown that only around 20% of fatalities were caused by explosions. Other underground hazards, such as falls or ground and blackdamp, also represented significant hazards to miners. In response it was recommended that a set of general safety rules be produced for legal enforcement by the inspectors across all coal fields. These were to be supplemented by Special Rules applicable to an individual colliery or local group. Responding to this recommendation in respect of the occurrence of explosions and blackdamp, the subsequent Coal Mines Act of 1855 included the specific safety rule requiring that an 'adequate' amount of ventilation be produced at all collieries to ensure that the work places were safe for working. At the same time, inspectors were given legal powers to enquire into the state of the ventilation in a mine.

Despite the efforts of the legislators, accidents continued to occur underground. For example, over the ten years from 1855 there were approximately 700 fatalities caused by explosions. As a result, a Royal Commission was set up to enquire into the causes of accidents in mines. Its report (5) was published in 1886. Once again this considered the problem of mine ventilation and the measurements associated with ensuring its proper operation. It was stated that whilst it was not possible to suggest a minimum air flow quantity that would ensure that each mine remained safe from explosions, measurements of the air flowing in each split of the current should be taken on a regular basis. This recommendation was accepted by the Government and embodied in a new Coal Mines Act of 1887. This made it a requirement that the quantity of air flowing in each split of the air current be measured at least once a month. The result was to be entered in a book kept at the colliery specifically for that purpose.

In 1906 another Royal Commission was set up, this time to review the workings of the 1887 Coal Mines Act. One of its findings of relevance to these discussions was related to the use of the word ‘adequate’ to define the minimum acceptable standard of ventilation underground. During the presentation of evidence the Mines Inspectorate noted that although may fatalities were arising from explosions of firedamp resulting from defective ventilation, this phraseology was so weak as to make it difficult for them to obtain subsequent convictions for contravention of the law. Eventually the Commission concluded that in any future legislation adequacy should be determined by reference to the concentrations of gases found within the underground environment that influenced the well being of those employed therein. More specifically, they recommended that the maximum level of firedamp above which men should not normally work in be set at 2.5%. Concerning the blackdamp gases, carbon dioxide and oxygen, the maximum allowed concentration of the former was recommended as being 1.25% and the minimum of the latter 19%.

The concept of defining ventilation standards through specified gas levels was later included in the Coal Mines Act of 1911. It also contained a provision that allowed for the production of rules specific to particular underground operations. These could be introduced by the Secretary of State without the need to produce a completely new Act of Parliament. In 1913 one such was issued specifying the points in a mine at which air flow measurements were to be taken (6).

More recently, the Mines and Quarries Act, 1954 states that it is the duty of the colliery manager to ensure that adequate ventilation is produced in all parts of a mine to dilute noxious gases, and provide enough oxygen to breathe. For the purposes of the Act the ventilation is considered adequate if the general body of the air contains less than one and a quarter percent carbon dioxide, or more than nineteen percent of oxygen. If the concentration of methane is allowed to rise above two percent men are to be withdrawn from the part of the mine affected.

The Coal and Other Mines (Ventilation) Order, 1956 gives the locations at which statutory air flow measurements are to be taken, and their frequency. The measurements must be taken:

a) In every intake airway starting at the shaft;

b) In every split of the air current;

c) In any part of the mine where a determination of methane content is made;

d) At the intake to any part of the mine containing a working place not requiring methane determinations.

They must be made at intervals of not more than thirty days, except ‘c’ where one is required to be taken each time a firedamp determination is made.

Clearly, so long as the above regulations or their derivatives are in force, it will remain a requirement for colliery managers, or their nominees, to measure air flow underground on a regular basis. However, such discrete measurements provide no indication of the state of the ventilation in between times. The advantages of employing continuously operating instruments to overcome this problem were recognised as long ago as 1852 (7). In this instant the aim was for such systems to be installed at strategic points on a mine’s network. By comparing successive readings an Inspector could ensure that an adequate supply of air had been maintained through the workings over the period between his visits. In modern times the value of continuously operating instruments as an aide to proactive system management has been recognised by the colliery operators themselves. As described in Chapter 3, this led the National Coal Board (NCB) to invest in the development of sophisticated computer controlled monitoring schemes that were not only capable of monitoring air flow, but also a range of other variables critical to underground safety.

As the benefits to be gained from providing coal mines with effective and efficient ventilation systems became better appreciated, so occasions have arisen where special air flow measurements are required that can not be reliably obtained using the methodologies to be described for more general purposes. Examples include the detection of low speed air leakage through broken ground between roadways and the assessment of human comfort in hot and humid conditions. The various specialised requirements that have occurred and the methodologies applied are described in Chapter 5.

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Part 1 The development of the methods to measure air flow in mines

Chapter 2 The routine measurement of air flow in mine roadways

This chapter describes the development of underground air quantity measurement techniques intended for routine use. Included within this classification are those applied by the manager to ensure that the mine is being properly ventilated, latterly in accordance with his statutory responsibilities. In modern coal mining, the results may also be used as boundary conditions in computer based ventilation models as an aid to ventilation planning.

When quantity assessments are being used to identify when changes occur in the flow at a number of discrete locations, a high degree of measurement accuracy is not necessarily required. Instead the results need to be 'repeatable'. This means that each bears a fixed, but not necessarily known, relationship to the 'true' quantity. Information as to the state of a ventilation system gained from a comparison of repeatable results from differing sites is unlikely to be reliable.

For inputs into the ventilation system modelling programs, or when it is required to compare the flow at different underground locations, the measurement results must be 'accurate'. This means that they bear a fixed and known relationship to the 'true' quantity flowing along a roadway.

Before the introduction of the 1887 Coal Mines Act it was largely left to the discretion of the mine officials when, or even if, measurements of air flow were taken underground. After, it became a legal requirement that they be taken on a monthly basis in all mines. The results were to be entered in a book with the intention that the information it contained would enable the Inspectors to determine at a glance the state of the ventilation and show if any serious changes in the air flow pattern had occurred. In practice, it was found that few mine officials understood the reasons why air flow measurements needed to be taken at all, simply considering it a legal duty (1). The result of this ignorance was that the results were rarely accurate and therefore useless in achieving the desired aim..

Whilst it has been speculated in Chapter 1 that the earliest air flow measuring systems used routinely in underground probably involved the injection of light tracers into the air current, hand held mechanical anemometers suitable for coal mine use became available during the fist half of the nineteenth century. These included the 'swinging plate' and 'rotating vane' types described in Chapters 7 and 8. The latter are like small windmills, with the wind speed being determined from their rate of rotation.

One of the problems with all these flow measuring devices is that they all show speed rather than the required quantity. Further, relative to a mine roadway they are effectively point sensors. In response to these shortcomings the common practice adopted is for the average wind speed in the roadway to be determined and then multiplied by the cross sectional area to give quantity. If a uniform velocity profile is assumed, the required average is simply the speed at any one point. Such can be easily obtained using any of the anemometers described. However, as early as 1849 it was being noted (2) that friction of the air against the rough walls produced a non-uniform flow pattern and that errors could occur if this was not taken into account.

In 1838, Combes (3) described how he had used a rotating vane anemometer of his own design to determine the average wind speed across a mine roadway. This involved using the instrument to take a number of separate speed measurements. The required result was taken as being the arithmetic mean of the individual readings.

Over the years, this method has been refined to become that accepted for use when measurements with a high level of precision are required, hence its given name of 'precise traverse'. In one example of a modern implementation a cross-section would be divided into about twenty sections using wires stretched across the roadway. An anemometer is then used to measure the speed in the middle of each. The required roadway wind speed is the average of the results thus obtained. With it taking about twenty five minutes to complete the traverse, the method is generally considered too laborious for routine use.

As will be seen from Chapter 8, the indicators on modern vane anemometers are effectively rotation counters where the impacting wind speed is determined from the number of revolutions completed in a measured time. This provides them with the important characteristic of being able to show the result averaged over extended periods of time, possibly several minutes. Soon after the introduction of the precise traverse it became apparent that this attribute of vane anemometers could be used to shorten the precise traverse application time. For example, in 1875 a measurement methodology was described (4) in which an anemometer was moved along a zigzag path of the shape shown in Figure 2.1 with pauses at the crosses. The desired average wind speed was given by dividing the number of vane rotations completed during the traverse by the time taken. Later (5), the pauses were removed and the instrument was moved at a uniform speed over the path. The total measurement time in this instance was only about two minutes. With both methodologies a calibration formula would have been required relating vane rotation speed to wind speed.

In 1880-1 it was concluded (5) that the results provided by the continuous zigzag traverse were 'trustworthy'. Despite the absence of any apparent justification for this statement, the method's simplicity and speed of use led to its widespread adoption for routine ventilation surveys in British coal mines.

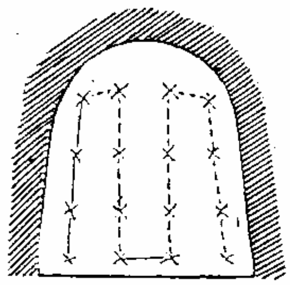

Figure 2.1 A zigzag anemometer traverse of 1875 (reproduced by kind permission of the Colliery Guardian)

A review of the application of the zigzag traverse published in 1939 (6) recommended that, rather than being held in the hand, the anemometer should be mounted on the end of a long rod and held upwind of the observer. This would minimise the errors introduced by his presence. As regards to the choice of measurement site, it was suggested that a uniform stretch of roadway be used to avoid the presence of air turbulence. It had been shown, say the authors, that errors of up to 10% could occur if vane anemometers were used in fluctuating air flows. No details are provided as to the origin of this data.

In the early 1950's Swirles at Nottingham University and Teale at the NCB's Mining Research Establishment (MRE) (see Appendix I) carried out two comprehensive and quantitative investigations into the use of rotating vane anemometers to measure air flows in coal mines.

Swirles showed (7), amongst other things, that the instrument reading was not affected by the presence of the observer taking the measurements provided it was mounted on the end of a rod at least 5 ft (1.5 m) upwind. He also showed that if the yaw angle (angle between the vane's axis of rotation and the direction of the wind) was less than about 20^{o} then the error in speed reading from this source was less than ±2.5%. During a traverse, the linear velocity of the anemometer is added to that of the wind. Swirles showed that to ensure that this did not lead to a false reading, for air speeds less than 2 m/s (400 ft/min) the traverse velocity should be less than 60 ft/min (0.3 m/s).

In his report (8) Teale commented that the work of Swirles had been mainly concerned with the repeatability of vane anemometer readings. This, he said, gives no indication of the overall accuracy of the results. To overcome this shortcoming, the new tests were carried out in a surface gallery and involved making comparisons between the air quantity results obtained using precise and zigzag traverses against a 'true' value. This was provided by a calibrated orifice plate flow meter connected to the gallery inlet. The results revealed little difference between the quality of the results provided by the two different traverse methodologies, despite the fact that the more laborious precise version was supposed to be more accurate. From the tests the expected accuracy of each traverse result was found to be within the range 5 to 23%.

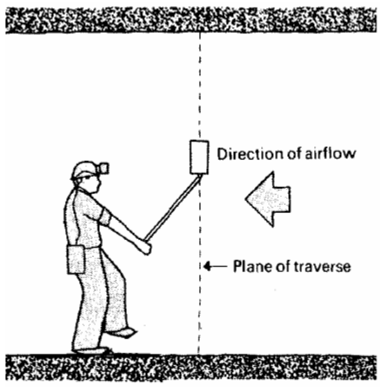

Figure 2.2 Taking a zigzag traverse

Subsequent to the publication of the results of Swirles and Teale, the NCB issued its Colliery Ventilation Officer's Handbook (9). In two editions, it gave details of the methods to be used to measure air flow in underground mine roadways. For routine purposes, the zigzag traverse was suggested. The anemometer was to be mounted on the end of a rod at least 1.5 m long and held at right angles to the roadway axis during the traverse, as shown in Figure 2.2. It was to be moved along a path of the form shown in Figure 2.3, with the linear speed being less than 0.17 m/s in wind speeds up to 2 m/s and 0.33 m/s above this. To minimise the possible effects of air turbulence, the measurements were to be taken, if possible, a minimum of twenty roadway widths from any bends or junctions. At each site, the average of four traverses was to be taken, discarding any that deviated from the mean by more than about ±5%.

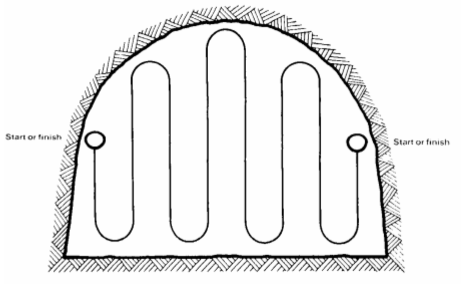

Figure 2.3 Zigzag traverse path

In recognition that locations may occur underground where the wind speed is less then the threshold of the available vane anemometers, (9) suggested that a safe chemical smoke be used in these circumstances. The method described is similar to one dating from 1835, only then smoke from gunpowder was used. A further description of these flow measurement methodologies is given in Chapter 6.

As noted above, the quantity of air flowing in a mine roadway is calculated by multiplying the traversed wind speed by its cross sectional area. In (9) it is suggested that the latter be calculated from a dimensioned sketch of the site, showing obstructions such as fixed plant. For details of more sophisticated roadway area determining techniques reference is to be made to (10)(11).

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Chapter 3 The use of fixed air flow monitors in coal mines

This chapter describes the use of anemometers that are permanently installed underground in coal mines to continuously monitor the flow of air at a particular location. In all cases they measure wind speed. Thus to obtain an indication of quantity, the reading often required, after installation a zigzag traverse must be conducted to determine a 'position factor' relating the two.

Permanently installed anemometers were seemingly first used to monitor air flow over mine ventilation furnaces. These consisted of either a crude windmill, or a piece of wood suspended by a string. The furnaceman was given instructions to keep the flow of air, registered by the rate of rotation of the windmill, or inclination of the piece of wood to the vertical, constant. Writing in 1876, Dickinson states (1) that such indicators had been used 'since time immemorial'.

An increasing awareness of the importance of ensuring that the whole mine was being properly ventilated led to the use of fixed anemometers at other locations underground. In 1851 Hedley (2) described how a suspended paddle type anemometer was used to highlight variations in air flow rate. These caused the device's deflection from the vertical to change.

In 1852 a report of the House of Commons Select Committee on Coal Mines (3) recommended that three anemometers be installed underground. One each was to be at the bottom of the upcast and downcast shafts and one at the extremities of the workings. The intention was that the newly established Mines Inspectorate could use the indications provided as checks to ensure that the air flow was at the desired level and had been maintained between visits. The instrument suggested for use was Biram's rotating vane anemometer (see Chapter 8). With this apparatus, the number of vane rotations completed was registered on a series of dials. Thus by noting the change in reading between visits, dividing it by the elapsed time and then applying a calibration factor, an indication of average wind speed could be provided. A clockwork driven recorder could also be fitted to the apparatus. This registered the day and time when the vanes had completed a predetermined number of revolutions. The chart had to be changed weekly, although dials on the anemometer were said to be adequate for up to two weeks continuous operation (4).

Despite the improvements in the safety of mines that would have resulted from the use of continuously registering anemometers, doubts were expressed (3)(4) over the suitability of Biram's apparatus in such a role. Many observers raised the point that these installations were useless because mine officials artificially quickened the air flow over them when the Inspector was not there. This resulted in misleadingly high indications.

To overcome this problem recording anemometers, or anemographs, were required. These provide a chart recording from which the air flow at any time can be determined, as opposed to the integrated value given by such as the Biram. Although anemographs were in use by meteorologists by the middle of the nineteenth century, those available were considered too complicated for collieries. One example of a mine ventilation recorder dating from around this period is Buxton's 'Ventilation Register' (5). No evidence has been found to suggest that this system found widespread application underground.

The need for ventilation recording instruments in coal mines was emphasised strongly in 1880 by Joseph Dickinson, Her Majesty's Chief Inspector of Mines. He cited a case where the lack of such apparatus had allowed a fan attendant to let his ventilator run slowly whilst he was across the road in a public house (6).

It seems apparent that the stated views of persons such as Dickinson eventually led to the introduction, from about 1880 onwards, of pressure recorders at ventilators. For a given mine it can be shown that the indication from such instruments is related to the quantity flow through the workings by a system 'aerodynamic resistance' (see Chapter 5). This is a function of geometry, including the length of the roadways between the upcast and downcast shafts and their area, perimeter and wall roughness. So, provided these remain fixed the ventilator pressure can be used as an indicator of the air quantity being passed through the workings

An early example of a pressure recorder is that due to Murgue (7) and dates from about 1898. This device may have been sensitive enough for it to be used in conjunction with pressure tube anemometers (see

Chapter 11) that were being introduced at around the same time. Such would have created a system capable of continuously recording the flow of air at sites remote from the ventilation furnace. Whilst some pressure tube based anemographs were installed in British coal mines, whether any incorporated the Murgue device.

To effectively monitor the ventilation of a large mine with fixed anemometers would require many instruments. If each was fitted with a local indicator, as would have been the case with the Biram, a considerable amount of manpower would be required to take readings from them all. To reduce costs it would be more advantageous if the indicators were all placed in close proximity to one another on the surface, even though the sensors were spread out underground. With such an arrangement frequent inspection of all the readings could enable potentially dangerous situation to be identified quickly. Further, the ease with which senior colliery officials could be assembled and appraised of the mine wide ventilation situation would facilitate the rapid initiation of remedial action. Such would not be possible if it was necessary for an individual to interpret the data from underground indicators, separated by what may be several miles.

During the latter part of the nineteenth century a number of remote indicating anemometers were developed for coal mine use. One of these was Hall's 'Telephonic Ventilation Tell-Tale' to be described in Chapter 9. In 1895-6 it was reported (8) as being installed at Park Collieries, Wigan. The indicator, connected to the underground sensor by wires, was placed in the mine manager's office. Although the advantages to be gained from having remote indicating anemometers were appreciated at such an early date, a lack of evidence of any widespread application leads to the possible view that the technology was not available to produce a reliable and safe system.

Between 1913 and the mid-1940's the demand for British coal fell by about 30%. Also, there was considerable debate as to the merits of nationalising the industry. The consequence was that the coal owners were reluctant to invest in the redevelopment and modernisation of their collieries. Thus by the late 1940's many coal faces were large distances from the pit bottom and at the end of roadways that were old, narrow and undulating. Such arrangements led to relatively inefficient mines that were costly to operate. The impact such a situation could have was graphically demonstrated when, during the winter of 1947 to 48, consequential fuel shortages led to a wholesale disruption of British industry. In an attempt to prevent this from recurring the Government, which now had control of the mines following nationalisation, initiated a program of reconstruction and modernisation. Primarily this involved increasing the use of underground machinery, both to cut the coal and to transport it away from the face. With these changes came a problem associated with increased firedamp concentrations and the appearance of other underground airborne hazards. As described by Unwin (9), in most cases the ventilation was an important method by which they were subsequently rendered safe.

As part of this post-war mechanisation in 1957 the NCB introduced a remote indicating system into its collieries. It was called ELSIE and was developed by Sargrove Electronics Limited (10). Using a form of frequency multiplexing, the status of switches controlling underground machinery could be displayed in a control room on the surface. By 1963 ELSIE had been extended to include safety transducers such as air flow switches (see Chapter 4). One of the major drawbacks of this system was that it could not be used to transmit analogue signals.

Despite heavy investment, a rapid rise in the productivity of the mining industry in the 1960's was not maintained into the 1970's. In response, the NCB's Mining Department and the Mining Research and Development Establishment (MRDE) (see Appendix I) began considering how increasing powerful computers that were becoming available at this time could be used as a means of rectifying the situation. Initially the program was directed toward the development of comprehensive monitoring schemes. At each colliery installation, the outputs from a multiplicity of underground measuring instruments would be transmitted via a digital data link to a computer based processor and display system sited on the surface (11). Early examples were designed for conveyor control. However, the concepts were later extended to include underground environmental monitoring. This led to the development and introduction of a wide range of electrical devices that were capable of continuously monitoring the relevant parameters, including firedamp (or methane), air flow, pressure, temperature and smoke. Being operational all the time, such a monitoring system clearly improved the safety of miners by ensuring that hazards were identified at an early stage of their development. In addition, a reduction in the need for men to take regular flow and other mine air samples released them for more productive duties.

Descriptions of the electronic air flow monitors developed for the NCB's comprehensive environmental monitoring systems are contained in Chapter 10. Typically they consisted of a flow sensor connected via a cable to a control unit. Both would be bolted to the roadway wall in such a way as to avoid them being damaged by the passage of men and materials. The control unit contained a display to show the measured flow. It was also provided with sockets through which an electrical analogue of the indication could be transmitted to the surface.

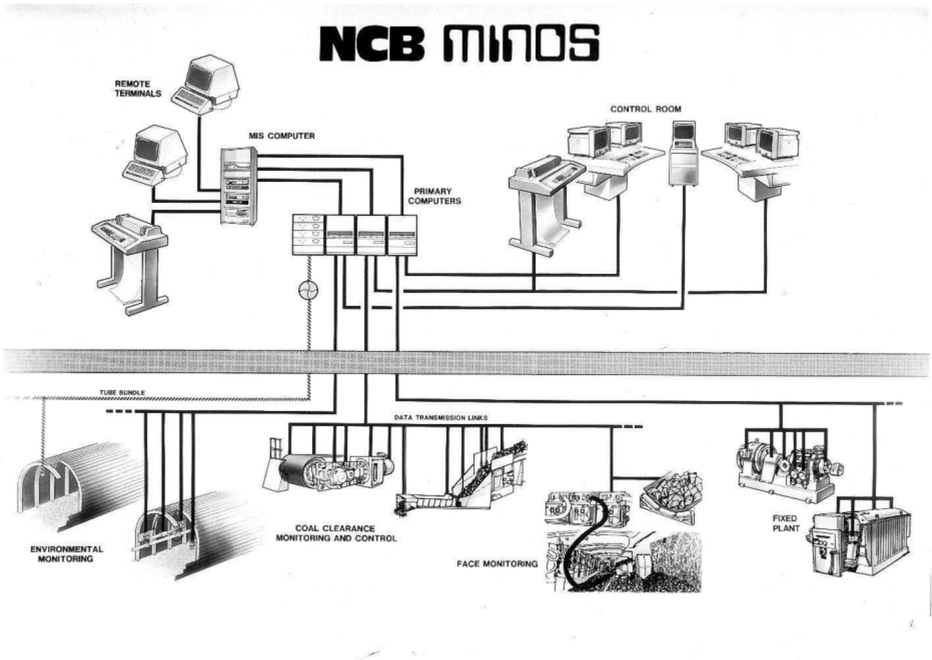

Figure 3.1 Schematic diagram of the NCB MINOS system (British Coal)

In 1974 a range of remote indicating environmental instruments were installed in a district at Brodsworth Colliery in Yorkshire. The output from each was transmitted to the surface along telephone cables for display on clockwork driven chart recorders. In the same year, the system was extended to other districts of the mine, with the transducer outputs being connected to a digital time division multiplex data transmission system. The environmental information was presented on a number of mains powered chart recorders. In about 1975 a computer was installed at Brodsworth to analyse and display this information (12).

The NCB, and latterly, British Coal's, standard computer system for analysing data is called MINOS (MINe Operating System). It is shown in schematic form in Figure 3.1. The transducer outputs are fed into underground outstations. These convert the analogue signals into a digital format suitable for transmission along a data 'highway'. From the surface, the underground outstations are sequentially interrogated and the data fed into a computer for analysis and display. The information gathered is presented on visual display units either in the form tables, or graphs showing trends. In the event of the computer sensing an alarm condition on any of the transducers, messages are automatically displayed telling the operator the location of the problem and the action to be taken.

An example of a layout of instruments in a MINOS installation on a longwall district is given as Figure 3.2. Typically, air flow monitors would be placed in the return airways. Other instruments would be placed in the ducts supplying air to blind roadways being driven into virgin strata. This particular aspect of air flow monitoring will be discussed in Chapter 4.

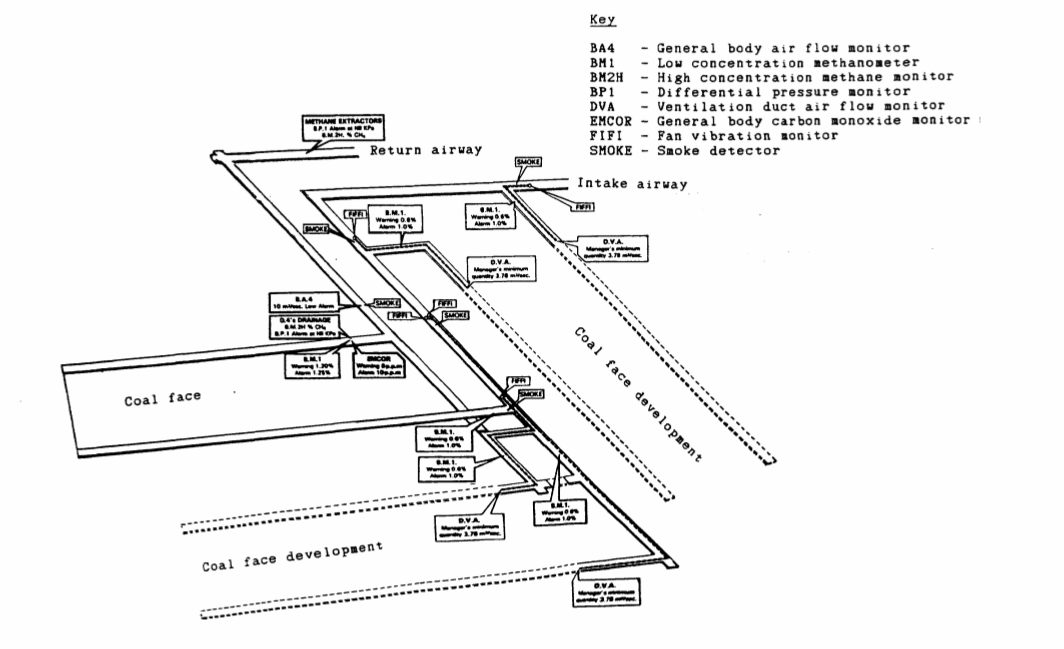

Figure 3.2 Example of the layout of instruments in an environmental MINOS installation (British Coal)

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Chapter 4 The measurement of air flow in auxiliary ventilation systems

When a single entry roadway, or heading, is being driven to exploit new reserves the law requires that the working face be adequately ventilated. This is achieved by fitting a continuous length of air duct along its length. One end is positioned a short distance from the face. The other is in the main mine ventilating circuit. Here an auxiliary fan used to either suck (exhaust) the foul air out of, or blow (force) fresh air into, the heading.

From documentary evidence it is clear that ducted air ventilation systems have been used in the coal and metal mines of this country since at least the middle of the nineteenth century, and probably a lot earlier. Since then it has become the practice, backed up by the requirements of legislation, to undertake periodic air quantity assessments. Due to problems associated with the accurate assessment of low flow rates, these are usually made in the duct rather than the heading. As with the larger mine roadways, here the linear air speed can vary widely over a duct cross section. This has necessitated the development of special measuring techniques.

Two methods of measuring the non-uniform flow in the ducts of mine ventilation systems are described by Hancock (1) writing in 1927. In the first, a Pitot type tube was used to take nine air speed readings over a single cross section and the average calculated. In the second, the flow in the duct was estimated from a single reading of wind speed measured using a vane anemometer. Although it was noted that the results obtained using the latter method were likely to be less accurate than those of the first, it was seemingly adopted for use within the coal mining industry at the time.

In 1955, at the request of the NCB's Chief Ventilation Engineer, MRE carried out an investigation into the methods of measuring air quantity flow in the ducts of forcing auxiliary ventilation systems using vane anemometers. The view was that accurate measurements at the intake and discharge ends of a duct would establish the quantities being taken from the main roadway and reaching the working place. Any differences would indicate the presence of leakage along the duct length, the reduction of which would increase the efficiency of a system. It would also reduce the cost of maintaining safe working conditions in the heading.

The results to the MRE investigation (2) showed that the average velocity of the air in a duct, and hence the quantity flow, could be obtained from the speed on the duct axis multiplied by a centre factor. At the discharge end of the system it was recommended that the measurement be made in the plane of the duct end. At the intake, it was found that it had to be downstream of a flow straightener. At both locations the centre factor was found to vary with duct size and flow rate.

In the first edition of the NCB's Colliery Ventilation Officer's Handbook (3) a method of measuring the flow of air in ducts similar to that developed by MRE was suggested. There were, however, some differences. Most notable of these was the suggestion that a single centre factor be used for all flow rates and duct sizes. For forcing systems this was 0.80 at the intake end and 0.85 at the discharge.

The MRE investigation did not cover exhausting systems. For these, (3) suggested that a flow straightener be fitted to the intake (at the working face of the heading). The anemometer was then inserted into the duct through a trapdoor on its down wind end. A centre factor of 0.80 was to be used. At the discharge end, the measurement of flow was to be made upwind of the fan, again using a trapdoor in the duct. A centre factor of 0.85 was to be used.

Rather than a vane anemometer, two methodologies using a standard Pitot static tube (see Chapter 11) were also suggested. The first obtained the average velocity from a single measurement multiplied by a centre factor of 0.85. Alternatively, a method quoted as being given by the Fan Manufacturer's Association could be used. In this, the average velocity was calculated from a number of discrete readings taken over a single duct cross section.

In the 1979 edition of the Colliery Ventilation Officer's Handbook (4) much of the detail concerning the methods to be adopted when measuring the flow of air in the ducts of auxiliary ventilation systems was left out for some reason. However, the publication still recommended that the centre factor method be applied, with a value of 0.80 being given.

In a later, but unpublished, review of flow measurement methods in auxiliary ventilation systems Hole (5) states that instances were found in which simultaneous readings taken by colliery and MRDE staff differed by up to 50%. Investigations into the possible sources of these large discrepancies showed that at collieries, besides those methods given in (4) a number of different ones were also in use. As illustrations, in some cases a centre factor of 0.85 was being applied to a measurement made on the duct axis whilst in others the maximum wind speed over the duct cross section was determined and a factor of 0.8 applied to give the average flow. According to Hole, a common method of measuring the flow at the intake end of exhaust ventilation systems was to traverse a rotating vane anemometer over the duct cross sectional area. No correction factor was thought necessary to convert the reading thus obtained into an indication of average wind speed.

Hole subsequently carried out his own investigation into the various duct air flow measurement methods found in use underground (5). It covered both forcing and exhausting systems. For the former, it was found that the 'best results' were obtained when the peak wind speed over a duct cross section was multiplied by a factor of 0.8. With exhaust systems the 'best' flow measurement results were achieved by traversing a rotating vane anemometer over the duct inlet. The average wind speed was then obtained by applying a factor of either 0.75 or 0.67, depending on the material from which the duct was made.

On the 12 April 1962 an explosion occurred in a heading at Tower Colliery, in Glamorganshire. Nine men were killed. Investigations later showed that on the day of the explosion the auxiliary ventilation fan had been stopped for about ninety minutes. This allowed the underground firedamp concentration to rise undetected to an explosive level. An electrical spark in a damaged cable ignited the gas (6).

One of the recommendations made in the official report was that all power to headings be automatically switched off in the event of a failure of the auxiliary ventilation. In response, permanently operating flow sensors began to be installed in ducts. As described in Chapter 13, some of the earliest examples consisted simply of 'low flow' alarms formed using a paddle suspended in the air current. This was joined to the operating mechanism of an electrical switch. Its state could be monitored from the surface using, for example, the ELSIE data transmission system.

One of the problems with flow switches was that they were incapable of showing the actual quantity of air flowing in the duct. In response to this perceived shortcoming, in the early 1970's MRDE began investigating the possible use of velocity pressure sensing and pressure transducers as a means of monitoring duct flow. The result was the production of the Duct Velocity Alarm to be described in Chapter 13. Versions of this apparatus eventually became available that produced a flow dependent electrical analogue for transmission to the surface via MINOS and local and remote alarm signals when it fell below a pre-set level.

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Chapter 5 The use of anemometers in special investigations and tests

In the history of coal mine ventilation and safety, special air flow measurement requirements have arisen that could not be fulfilled by the direct application of existing techniques and instrumentation. Some of the methodologies developed as a result are discussed in this chapter.

5.1 Testing of fans

Up to the about the mid-nineteenth century in those coal mines that were ventilated this was most commonly done by building large furnaces at the bottom of one of the shafts. However, the occurrence of explosions directly attributed to ignitions of firedamp by the flames led to the attempted application of mechanical alternatives, including air pumps, steam jets, and waterfalls. Eventually, steam and then electric driven surface mounted fans became almost universally adopted.

To investigate the performance of these new ventilators relative to those already being used, it was necessary for performance tests to be developed. As an example, for fans this would include measurements of the input power and the differential pressure and air quantity flow generated with a given aerodynamic load.

Considering fans, a discussion of how the differential pressure has been measured is, strictly, beyond the scope of this monograph. However, a brief mention will be included because it was the controversy over these that eventually led to standardised test methods that included the use of anemometers.

When ventilator performance tests were first conducted the form of pressure sensing head, its location and orientation to the flow varied between experimenters. Sometimes, if the desired results were not obtained using one arrangement, the readings were discounted as being ‘obviously wrong’ and a different one used.

In 1912, Watson (1) appealed for a universally accepted fan test method, suggesting that the Institution of Mining Engineers set up a committee to consider the subject. Eventually, in 1934-5, the first specification for a standard fan test was published (2). Shortly after, the British Standards Institution (BSI) formalised the situation by publishing BS 707:1936, The Testing of Mine Fans. This was later replaced by BS 848:1939, Testing of Fans for General Purposes. In 1952 the Fan Manufacturer’s Association felt that a review of BS 848 was long overdue and issued their own version (3). BS 848 was revised in 1980.

As with routine mine ventilation work, the quantity of air flowing through a fan is usually obtained by multiplying the average wind speed in the fan ‘drift’ by its cross sectional area.

In his plea for a standard test method, Watson (1) described tests in which he determined fan quantity using a rotating vane anemometer and the precise traverse described in Chapter 2. However, he noted that it would have been better if the anemometer were scanned continuously over the area, pausing for a short period in each of the subsections into which the roadway had been divided. From the results of Teal and others, it appears as though it would have made little difference to the accuracy of the results obtained.

The fan testing standard published by the Institution of Mining Engineers (2) also adopted the precise traverse for the air quantity flow determinations. For this the area was divided into 2 ft (0.6 m) square subsections. If the air flow was to be measured using a rotating vane anemometer then the pseudo-continuous scan suggested by Watson was to be used. The pause in each subsection was to be at least ten seconds long. If the typical wind speed at the site was greater than 1000 ft/min (5 m/s), Prandtl or National Physical Laboratory (NPL) Pitot static tubes (see Chapter 11) could be used. The flow was calculated from the average of the speeds measured in the centre of each subsection.

It appears as though the first British Standard fan test specification, BS 707:1936, was probably identical to that issued by the Institution of Mining Engineers. The later examples, renumbered BS 848, have included alterations to the way in which the airway is divided up. They have also contained, for example, a new section dealing with the measurement of flow in circular ducts. For these, BS 848:1980 states that ten velocity readings are to be taken along each of two mutually perpendicular diameters. Rather than being uniform, their spacing is determined by the ‘log-linear’ rule. This has been shown to give the more accurate results. Reference to the use of rotating vane anemometers has also been removed from BS 848:1980. Instead, the flow of air is to be measured using a Pitot static tube.

According to relatively recently information from Morris (4), within the coal mining industry vane anemometers are used in the conduct of periodic checks on fan performance. However, the British Standard methods are always used for fan acceptance tests.

An alternative method of determining the fan quantity flow was developed by the NCB at MRE during the 1960's (5). In this a nitrous oxide tracer gas was injected into the air upwind of the fan. Samples taken at regular intervals on the downwind side were analysed in the laboratory for the gas and a graph of concentration against time after release plotted. The area under this curve was determined and a formula used to calculate the volume flow rate. This technique of measuring fan volume flow does not seem to have found general application in mines, probably due to its complexity.

5.2 The measurement of aerodynamic resistance

When a pressure difference is applied between the ends of an airway the resulting quantity flows is determined by a factor called in this monograph its 'aerodynamic resistance'. This is an energy loss term and, as noted in Chapter 3, depends upon the roadway geometry. If a ventilation system is formed from a network of large, smooth roadways it will have a low total resistance. This means that for a given applied pressure, a higher quantity of air will flow than if they are small and rough and the resistance is high. Also, the costs of maintaining safe conditions underground through the application of ventilation will be lower.

The concept of aerodynamic resistance as applied to coal mine ventilation networks was considered by Nicholas Wood in 1852-3 in Volume 1 of the Transactions of the North of England Institution of Mining Engineers, published (6). His idea was that it could be used to compare the state of the roadways at different underground locations. About two years later Atkinson (7) proposed that the ventilating pressure (P) of a mine be related to the quantity flow (Q) via:

$$P = RQ^2$$

where R is the aerodynamic resistance. In the practical application of this formula it was suggested that R be determined for a roadway on a regular basis by measuring the air quantity flowing and pressure drop along it. Any rise in the result with time would show that its condition was deteriorating. Atkinson also said that the ventilation of a whole mine could be studied in this way, presumably by taking measurements between the ends of main intake and return airways.

Although Atkinson's results do not appear to have found immediate application underground in coal mines on a routine basis, there was a continuing discussion of the subject. For example several workers conducted experiments to investigate the relationship between pressure and flow and how it was affected by roughness. In investigations conducted by Murgue (8) rotating vane anemometers and a twenty to twenty-eight point precise traverse were used However, finding this method too laborious he frequently reduced the number of sample points to four, only using larger surveys at the beginning and end of each test. Later, Hay and Cooke (9) used a Pitot static tube positioned in a special Venturi shaped section of their test gallery. The position factor for this layout was determined using a twenty point precise traverse.

In 1928/9 David and Davies (10) described the first complete mine ventilation survey carried out using the techniques suggested by Atkinson. In a later paper (11) it was suggested that in such a procedure the required air quantity flow measurements could be obtained using a rotating vane anemometer and a zigzag traverse. Alternatively, Pitot tubes or Velometers (see Chapter 7) could be used with a precise traverse. Further details concerning the conduct of ventilation surveys are given in (12).

The mechanisation of the coal mining industry that took place during the 1960's included the introduction of hydraulic roof supports and power operated cutters on the coal face. To investigate the aerodynamic resistance of these new lay-outs, recording pressure and wind speed instruments were required. In response MRE developed its type 813 electronic recording anemometer described in Chapter 10. Unfortunately, problems with its reliability in the harsh conditions found underground meant that much of the face resistance work had to be conducted using hand held anemometers. However, the experience gained with the 813 helped in the subsequent development of the continuous air flow monitors for use in MINOS.

5.3 The detection of leakage

A mine ventilation circuit consists of a number of interconnecting air ways driven through solid ground. To ensure that all underground locations receive their quota of fresh air, wooden or cloth sheet partitions are erected to guide the current along the desired course. These are sometimes fitted with doors to allow the passage of men and materials from one part of the mine to another. When a district has been worked out explosion-proof stoppings are built across the intake and return airways to seal it off.

If a pressure difference exists across a door, stopping, or the fractured ground between roadways undesired air leaks will occur. Those around doors may result in one part of amine being starved of air. Leakage through broken ground that contains carbonaceous material can lead to the onset of spontaneous combustion. If this is left untreated an open fire can develop. To avoid both such events it is clearly important that any leaks from the main air current be detected quickly. Unfortunately the low flow rates typically involved have precluded the use of conventional anemometers and special techniques have had to be developed.

Leaks around doors and partitions can be detected by either listening for the hissing sound made by the air as it passes through the gaps or by observing the motion of chemical smoke clouds (see Chapter 6).

Possibly the greatest advances in leakage detection came with the introduction of modern tracer gas techniques into British coal mines. In 1963 Catchpole (13) described how helium had been used to detect the movement of air in a sealed off district. This was the site of a fire that would not burn itself out. Gas injected behind a stopping on the intake side of the mine was eventually detected behind one on the return. This showed that fresh air was leaking into the sealed off area allowing the fire to continue burning. As described in Chapter 6, nitrous oxide (N_2O) has also been used for mine leakage detection, although more recently sulphur hexaflouride has become the preferred tracer. Examples of its application are provided by Wann et al (14). In one of these, an air flow rate of only 22 ml/s was detected.

5.4 The measurement of the ability of miners to keep cool

A working human generates heat internally as food is oxidised to produce energy. If this is not lost to the environment, and the body temperature is caused to rise outside its preferred range, the brain reduces the activity level of the body. The result is that working men begin to feel tired and their productivity falls. Also it has been shown (15) that they are also subject to an increased risk of accident. Excess body heat is primarily lost through the skin surface by conduction and the evaporation of sweat.

It was known in the nineteenth century that mines got hotter the deeper they were. Using the data available it was even feared that this would limit the working depth of collieries to 4000 ft (1219 m).

In 1920/21, the third report of a committee set up by the Institution of Mining Engineers to look into the problem of working deep mines was published. This revealed (16) that the rate of cooling of a hot moist body was related to the speed of the air passing over it and the relative humidity of the atmosphere. The investigations that led to this conclusion had been carried out on a number of coal faces and had involved the use of the kata-thermometer developed by Hill (see Chapter 12). This device was similar to a conventional thermometer, with the exception that it had an enlarged bulb and was only calibrated from 90 to 110^{o}F. Developed as an indicator of human comfort in hot environments, it could also be used as an anemometer that was sensitive to low wind speeds. For both applications the bulb was first heated to above ambient, exposed to the air stream and the time taken for the thermometer to cool between the two graduations measured. A complex calibration formula was then used to give the wind speed.

Once the importance of even low wind speeds in the process of keeping cool in hot environments had been demonstrated, it was necessary to gather more information about the actual conditions found in coal mines. This required the use of an anemometer that could accurately measure wind speeds in the region of 0.03 to 1 m/s. In a discussion paper on the problem, Rees (17) said that this was below the response threshold of both conventional rotating vane and pressure difference anemometers. Further, the kata-thermometer was difficult to use. Following a description of a sensitive swinging plate anemometer (see Chapter 7), mention is made of a new hot wire anemometer that had been specially developed to measure low wind speeds in coal mines (see Chapter 12).

Although miners can be kept cool by a current of air, a report to the Monmouthshire and South Wales Coal Owner's Association (18) warned against the use of wind speeds that were too high. Under these conditions the miners may become too cold to work efficiently, or dust may be swept up into the air stream. Not only can the latter be a nuisance, but it is now known that its inhalation can lead to a fatal disease of the lungs called pneumoconiosis. The report recommended that a wind speed in the range 0.8 to 2.2 m/s be maintained to provide the necessary cooling power without creating a dust problem. Flow rates in this range can easily be measured using conventional rotating vane anemometers.

The existence of potential health and safety problems relating to heat and humidity has been acknowledged by the legislators. Contained within the Mines and Quarries Act, 1954 is a statement of the desirability of ensuring that the working conditions are 'reasonable so far as regards the temperature and humidity of the atmosphere'.

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Part 2 The development of the apparatus to measure air flow in mines

Chapter 6 The use of tracers to measure air flow in mines

For the purposes of this monograph, a tracer is defined as being a substance, or body, which, when introduced into a fluid stream, allows its otherwise invisible movements to be observed. To achieve this the tracer must be both distinguishable from its surroundings and capable of moving with the same speed as the current into which it has been injected.

6.1 Visible tracers

It has not been found possible to ascertain precisely when visible tracers were first used to detect or measure air flow in coal mines. However, descriptions of a number of methodologies available by the mid-nineteenth century are provided by (1). At this time, those used included hand-held candles and smoke.

The simplest method of using a lighted candle to provide an indication of air flow underground involved holding it in the air current. If the flame was extinguished in less than a minute the flow was considered sufficient. The description states that 'pit' candles were used, of which there were forty-five to the pound weight (unit weight about 10 g).

Another method required that an observer hold a lighted candle at arm's length and walk along a roadway at the same speed as that of the air current. The speeds were matched by ensuring that the flame always burned vertically. A watch or sand glass was used to determine the time taken to traverse a known distance, thus enabling the wind speed to be determined (1)(2). By this methodology wind speeds between about 30 and 400 ft/min (0.15 and 2.0 m/s) could be measured. At lower flows the air current did not deflect the flame, whilst at higher values the need for the observer to run meant that his motion was unsteady (2)(3).

Smoke produced by the explosion of a small quantity of gunpowder was another tracer widely used to measure air flow in coal mines in the nineteenth century. A uniform section of roadway was chosen and two marks made on the wall a known distance apart. A short distance upwind of the first of these a small quantity of gunpowder was ignited. The time taken for the smoke to pass between the two marks was measured using a watch (4). The wind speed was calculated by dividing the distance travelled by the time taken.

The use of gunpowder smoke to measure air flow in mines was investigated in detail by Atkinson and Dalglish (3). Their results were published in 1861 and enabled a set of rules to be drawn up which were intended to minimise the errors in the final wind speed estimation:

a) Always use 1 cu inch (16 cc) of gunpowder;

b) Only use the method in wind speeds greater than 100 ft/min (0.5 m/s) and less than 500 ft/min (2.5 m/s);

c) Choose a distance such that the time taken for the smoke cloud to cover it is between 12 and 30 seconds;

d) Explode the gunpowder 10 ft (3 m) upwind of the first mark.

Precautions a) and d) were designed to minimise the effects of the impulse caused by the explosion of the gunpowder, whilst b) and c) were apparently intended to limit the effects of smoke dispersion and to ensure that the cloud's leading edge was clearly defined at both marks.

The hazards associated with the use of candles and gunpowder in coal mines were recognised from an early date and their use discouraged in mines where firedamp occurred. By 1861 such methods of measuring wind speed were being gradually replaced by Biram's rotating vane anemometer (see Chapter 8). Unfortunately, shortcomings in the performance of this instrument, notably its relatively high threshold of response, meant that there was always a requirement for some form of tracer.

In 1708 Derham had mentioned (5) that the speed of the wind could be determined from observations of the motion of woolly seeds and feathers as they floated on the air current. This type of light tracer was also used in coal mines along with hydrogen filled balloons. From the comments made in the literature, however, it appears as though they were not popular. This was because, for example, the woolly substances tended to stick to the damp mine roadway walls and the balloons bounced from side to side. In both cases, this made it difficult to estimate the distance travelled in the measured time.

A relatively safe source of ‘smoke’ became available for ventilation engineers when, in 1923, Katz and Bloomfield described (6) the first of what became a series of chemical based generating systems. Rather than carbon particles of conventional smoke these produced a mist of fine sulphur trioxide droplets. The generating mechanism was a reaction between atmospheric water vapour and fuming sulphuric acid. This was held on pumice stone contained in an open ended glass tube.

To use the apparatus, an aspirator bulb was fitted to one end of the tube. This enabled air to be sucked in from the general body and blown through the porous filling. Here any atmospheric water vapour reacted with the acid. The resulting sulphur trioxide emerged from the other end of the tube as a dense white cloud resembling smoke. Katz and Bloomfield used the apparatus to measure air flow in US mines where naked lights were not permitted.

In 1931, Hinsley and Mitcheson (7) reported the use of an ammonium chloride smoke generator to investigate air flow patterns in British coal mines. The equipment was probably similar to that described later by (8). This consisted of two vessels, one containing hydrochloric acid and the other ammonia. These were linked to each other and the atmosphere by pipes. An aspirator bulb was used to bubble air first through the hydrochloric acid and then through the ammonia. The reactions that took place formed ammonium chloride. This emerged from the last vessel as a dense white cloud resembling smoke.

One further chemical smoke apparatus, which was similar to that of Katz and Bloomfield and also used atmospheric moisture to produce the mist, was described by McElroy (9) in 1935 and is shown in Figure 6.1. This time the pumice carrier was soaked in titanium tetrachloride and the output was a dense white cloud of hydrochloric acid vapour. The same chemical reaction has since been used in commercial smoke tubes marketed in this country by MSA (Britain) Limited for at least twenty-five years.

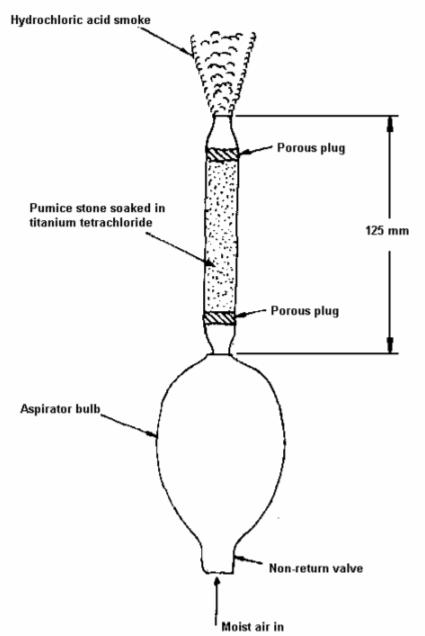

Figure 6.1 McElroy’s chemical smoke tube

Both editions of the NCB’s Colliery Ventilation Officer’s Handbook suggest that chemical smoke be utilised to measure low wind speeds, that is below about 0.3 m/s. The method involves making two marks a known distance apart along a straight and uniform stretch of roadway. One operator, standing upwind of the fist of these produces a ball of smoke in the centre of the road. A companion then measures the time taken for the cloud to cover the distance between the two marks, enabling the wind speed to be calculated. Since this technique only gives the air speed in the centre of the roadway, a correction factor must be applied to give the average over the cross-section. The upper limit of this method is left to the discretion of the operator. However, in sluggish flows the smoke cloud becomes too dispersed for its true beginning or end to be seen. In high flows, the cloud becomes dilute and invisible.

6.2 Gaseous tracers

As an alternative to solid tracers, gases have also been used to measure air flow underground in coal mines. One of their advantages is that some are detectable at very low concentrations, allowing them to be used in conditions under which smoke becomes too diffuse to be visible.

One of the earliest recorded uses of a gaseous tracer in a British coal mine was by Howe (10) in 1870. He used sulphuric ether (diethyl ether), a volatile substance with a smell not usually found in mines, to measure the flow of air in an upcast shaft. A small bottle of the liquid was broken at pit bottom and the time taken for the smell to reach an observer on the surface measured. The air flow could then be calculated knowing the depth of the shaft.

In 1875, the Colliery Guardian (11) reported that a Mr Arnold had made similar use of ammonia. However, the presence such ‘evil’ smelling substances underground was not without its problems, particularly when the effects on those employed underground were considered. On this subject, the same article states that the presence of the vapours ‘..is a great annoyance to the work people, irritating their lungs and tempers.’

After these references, the use of tracer gases to measure air flow seems to have been largely forgotten. In about 1943, Majorcas re-introduced the practice in other industries, and, along with Voice, developed the techniques that are used today (12).

In the late 1950’s, the need arose within MRE for a method of measuring air quantity flow with a higher degree of precision than was considered possible using rotating vane anemometers. To meet this requirement two gas tracer based methodologies were developed using nitrous oxide (N_2O). This substance was chosen because it did not occur naturally in mine air, was considered to be non-toxic and could be accurately detected at low concentrations in air (13).

One of the MRE methods was designated ‘steady release’. With this nitrous oxide was injected into the air stream at a known and constant rate. Downstream, where the gas was considered to be fully mixed with the current, an MRE sampling pump was used to take periodic samples. Following analysis in a laboratory on an infra-red gas analyser, the quantity flow rate was obtained by dividing the rate of injection by the detected nitrous oxide concentration when it had reached a steady value. This technique was suitable for use in the higher air flows

The other method was called ‘pulse release’. This involved injecting a known mass of tracer into the air stream. Periodic samples of mine air were taken and a graph of detected concentration versus time plotted. Provided there was no leakage of into or out of the test section, the quantity flow could be calculated from the mass of gas injected and the area under the graph. This method was used at the lower flow rates where it was impractical to inject sufficient tracer into the air stream to achieve a steady concentration.

Between 1959 and 1962 MRE used the nitrous oxide tracer gas to measure the flow of air through mine ventilating fans. Later, in 1965, experiments were conducted to see if it was suitable for the very low leakage rates through stoppings. Despite some difficulties in obtaining adequate mixing of the tracer with the air, they did prove successful (14).

One of the problems with nitrous oxide gas is that it causes temporary anaesthesia, albeit in large concentrations. It can not, therefore, be considered as being particularly suitable for use in a coal mine. As an alternative, in 1963 helium was used to investigate the flow of air into a supposedly sealed off district of a mine (15). This gas was reported chosen because it could be easily detected using the chromatographic equipment available in the laboratory at the time.

More recently, sulphur hexaflouride (SF_6) has been used as a tracer gas for mine ventilation work. This has the advantages that it can be accurately detected at low concentrations and is believed to be non-hazardous.

A very early application of sulphur hexaflouride to measure air flow in coal mines was reported by Thimons et al in the USA in 1974 (16). The gas was used for the first time in this country by Wann (17) in 1975. Here the desire was to detect very low flows through stoppings in mines. In an example given, the pulse release method was used with an estimated leakage rate of 22 ml/sec. It took four weeks before 92% of the released gas was collected. Subsequently sulphur hexaflouride has been used by the Mining Research and Development Establishment (MRDE) to detect flow in wastes and methane drainage bore holes. The migration of firedamp through strata has also been investigated using this tracer (18).

Sulphur hexaflouride tracer gas is not suitable for routine use in coal mines due to a need for complicated analytical apparatus.

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Chapter 7 Plate anemometers

When a flat plate, or other form of solid body, is exposed to a current of air it tends to move along the same direction. When this motion is opposed by a force that increases with displacement from the initial equilibrium position, the distance moved can be related to the incident wind speed. Alternatively, if a force is applied to prevent the object moving in the first place, then the magnitude required is also related to the incident wind speed. This chapter discusses the development of anemometers and anemographs for coal mines that operate on these general principles.

7.1 Freely suspended plate anemometers

With the anemometers to be considered in this section, the force that opposes that of the wind on the sensing object is generated by gravity as the system moves away from its 'still air' position. Thus the observable variable from which the desired reading is obtained is an object displacement. A typical instrument would consist of a flat plate, freely suspended from a hinge along its top edge. With such a 'swinging plate' anemometer the indication of wind speed is provide by the plate's deflection from the vertical.

Middleton (1) suggests that the freely suspended plate anemometer was probably invented by Leon Battista Alberti in about 1450. Mounted on a weather vane, the device was intended for meteorological use. In about 1500 Leonardo da Vinci sketched his own swinging plate anemometer. Later, the Transactions of the Royal Society in London for 1667 (2) also mention a swinging plate anemometer, the re-invention of which has been attributed (1) to Sir Robert Hooke.

The suspended flap type anemometers reported (3) to have been used in British coal mines consisted of pieces of wood suspended from lengths of string. These were fixed near ventilating furnaces to ensure that the correct air current was being passed through the mine at all times.

A more sophisticated anemometer whose use was also associated with colliery ventilator monitoring was devised by Sir George Cayley in 1849 (4). This was apparently made for Sir Goldsworthy Gurney who was attempting to demonstrate that a steam jet ventilator of his invention was both safer and more efficient than the furnaces then being used. Evidence provided by reference (5) shows that the instrument was used underground.

Cayley's anemometer is shown in Figure 7.1. In this the sensing plate 'A' is suspended from two hinged arms. When exposed to an air current it was pushed backwards, deflecting the links. The angle of rotation was related to the incident wind speed. This was read off a graduated quadrant 'D'. To prevent the system from oscillating in pulsing flows, the motion of the beam was damped. One arrangement used consisted of an oar that was dragged through a water trough 'C'. However, this was thought to be unsuitable for potential underground applications and so an alternative was suggested. This incorporated a punctured silk bellows 'E' fixed to the end of the beam 'F'.

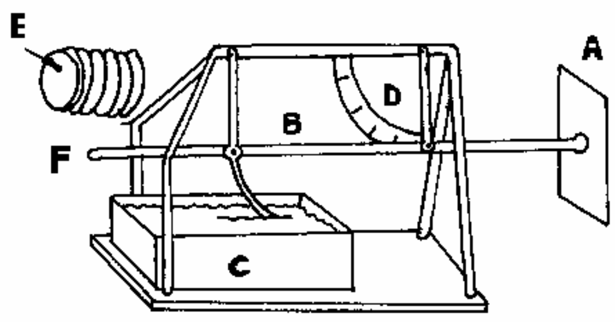

Figure 7.1 Cayley's anemometer

A swinging plate anemometer that seemingly found wide application in coal mines was developed by Joseph Dickinson between about 1852 and 1858. This is shown in Figure 7.2. In its original version it consisted of a sheet of oiled skin suspended from its two upper corners. On the downwind side was a quadrant, scaled from 20 to 700 ft/min (0.1 to 3/6 m/s), past which the plate was deflected by the force of the wind. A spirit level and sight were fitted to facilitate the alignment of the apparatus with the air current. Later, other versions were made with brass, mica or talc plates, giving alternative flow ranges. The anemometer was made by Casartelli of Manchester (6)(7)(8)(9).

At about the same time, other similar devices also appeared. For example, an anemometer of Phillips is said (10) to have used a semicircular plate, whilst that of Deveillez used a hemisphere (6).

In rapid air currents simple swinging flap type anemometers, such as Dickinson's, were found to vibrate continuously. This made them very difficult to read (7). The problem was partially overcome by Wild who, on a permanently installed instrument, connected a counter balance to the flap by means of chains passing over a series of pulleys. The friction of the system was intended to damp out any vibrations (6). No record has been located as to the effectiveness of this system.

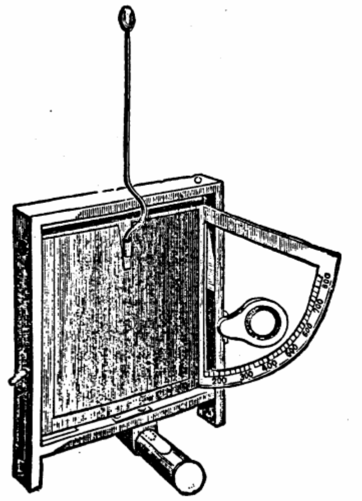

Figure 7.2 Dickinson's anemometer
(Reproduced by kind permission of the Colliery Guardian)

By the beginning of the twentieth century, the use of freely suspended plate air flow sensors in coal seems to have ceased. There was, however, a short revival of interest around the middle of the 1960's, when they were used to sense the flow of air in the ducts of auxiliary ventilation systems (see Chapter 13).

7.2 Spring balanced plate anemometers

In this type of anemometer the motion of the vane is opposed by the force of a compressed or twisted spring.

According to (1) one of the earliest anemometers of this type was developed by Bouguer in 1746. It consisted of a flat plate mounted in a box. When exposed to an air flow, this moved backwards, compressing a spring as it did so. The distance travelled could be related to the strength of the wind.

William Peace of Wigan invented what was probably a balanced plate anemometer for coal mines in about 1858. From the advertisement reproduced as Figure 7.3, it will be seen that it was intended for use in downcast shafts (11). The wind speed was estimated from the force acting on a piece of hanging wood indicated on a dial at the pit top. It is not known how widespread the use of this instrument was.

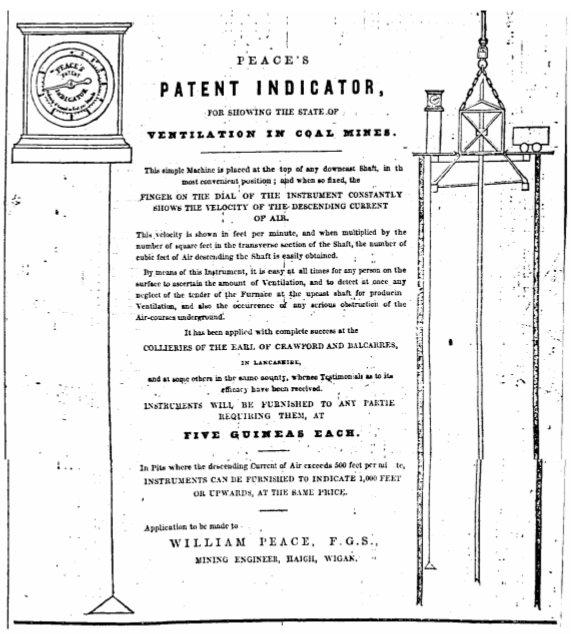

Figure 7.3 William Peace's plate anemometer
(Reproduced by kind permission of the Colliery Guardian)

Rees reported (12) the use of a sensitive balanced vane anemometer to measure wind speeds in the range 0.05 to 1.0 m/s on a coal face in 1927/8. The apparatus, shown in Figure 7.4, was designed by Casella Limited to Rees's specification. It consisted of a light vane suspended from a fine wire. This was deflected by the force of the air current. Any motion was opposed by twisting the suspension wire about its longitudinal axis. The applied force necessary to keep the plate in its vertical position was related to the incident wind speed. A dash pot was fitted to damp out vibrations.

The mining community was not particularly impressed with the ‘torsion’ anemometer. In an attempt to counter some of the criticisms, including making it simpler to use and more robust, Rees altered its design (13). However even this incorporated a fine, unprotected, suspension wire. On this basis alone, it can not be considered to have been suitable for general use in coal mines. Despite this, it is stated (14) that the anemometer had the advantage over other instruments of being able to measure wind speeds down to 0.05 m/s.

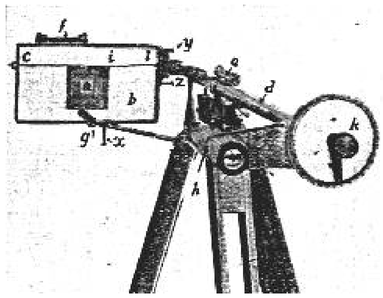

Figure 7.4 Rees’s torsion anemometer
(Reproduced by kind permission of the Institution of Mining Engineers)

A more robust balanced vane anemometer was invented, in the United States, by a Dr Boyle. Called the ‘Velometer’, it was widely used in British coal mines both for routine ventilation surveys and research. The anemometer was developed and marketed in this country from about 1938 onwards by Metropolitan Vickers Electrical Company Limited, of Manchester (15).

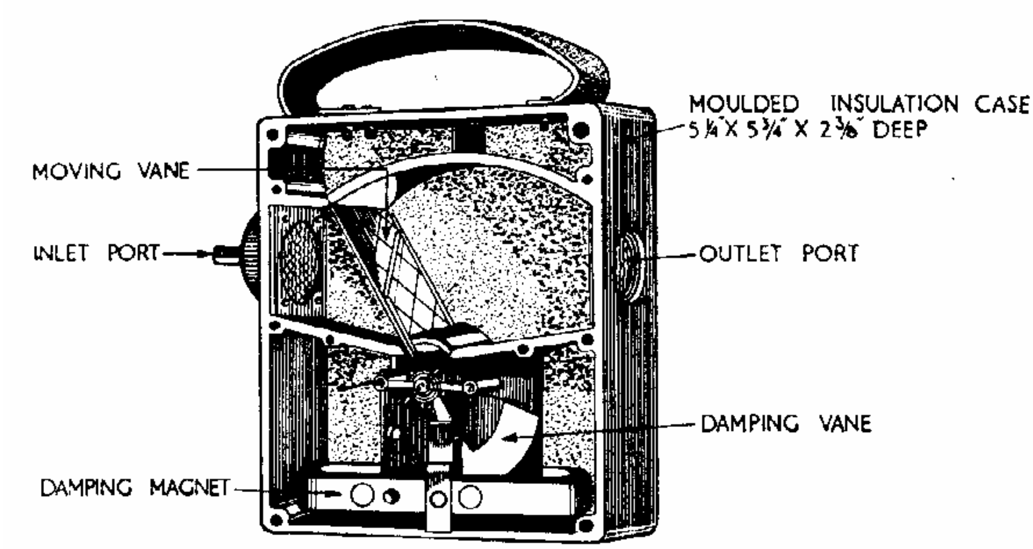

Figure 7.5 A cut away drawing of the Velometer

The Velometer is shown in cut away form in Figure 7.5. The flow sensor consisted of a light aluminium vane mounted in a shaped channel. A pointer (not shown) was fixed to the suspension axle and moved over a graduated scale. When the instrument was pointed into the wind, a flow of air between the inlet and outlet ports deflected the vane until a restoring force, generated by a coil spring, prevented any further movement. At this point the wind speed could be read off the scale. Instruments were available for use in flow rates up to 15 m/s. Special adapters were available that allowed Pitot tube type probes to be fitted. By this means the Velometer could be used for a wide range of other air flow duties, including as the measurement of flow in closed conduits (16).

7.3 Recording plate anemometers

As noted in Chapter 3, by the middle of the nineteenth century the Mines Inspectorate was becoming increasingly interested in providing themselves with continuous records showing the state of the ventilation in the mines under their jurisdiction. Initially, the possibility of using instruments developed for meteorological purposes was considered. However, it was concluded that they were unnecessarily complicated for coal mines (3).

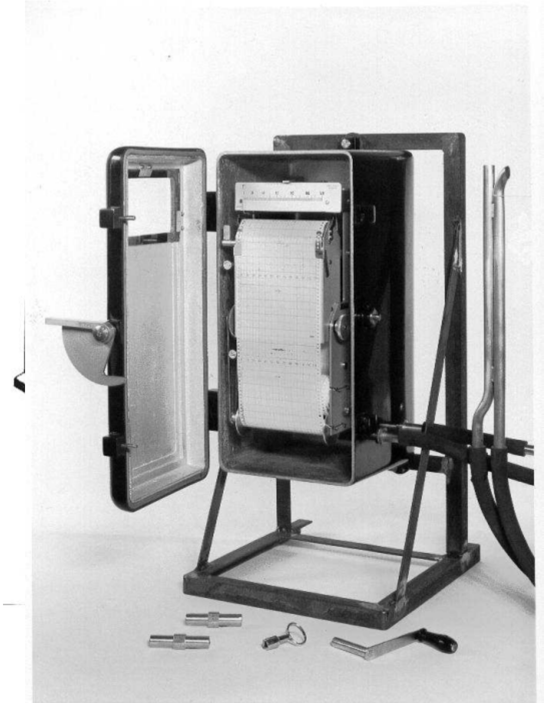

Figure 7.8 The Gothe anemometer
(Reproduced by kind permission of the North of England Institute of Mining and Mechanical Engineers)

An example of a plate type anemograph for coal mines is due to Buxton and dates from 1861. It is shown in Figure 7.6. Three flap type flow sensors (not shown on the diagram) were connected to the apparatus via hair wires. As the flow rate changed so pencils were caused to move up and down marking a paper chart. This was advanced by a water powered ratchet wheel to produce a continuous record of wind speed. Other features included indexing pointers to show the instantaneous reading and a bell that was rung periodically to remind the furnace man to attend to his duties. It is reported (17) that the apparatus was installed at Springwell Colliery near Stavely, Derbyshire.

Later, around 1938 and at the request of Dr. Wheeler of the Government's Safety in Mines Research Board, the Velometer was adapted for recording purposes. The apparatus, shown in Figure 7.7, consisted of a conventional instrument fitted with an extended pointer. This ran just above a clockwork driven paper chart. Periodically a chopper bar caused the pointer to press a carbon ribbon onto its surface, making a small dot. As the chart rotated a line was drawn representing the time varying wind speed. The air flow was sensed using a Pitot tube arrangement connected to the inlet and outlet ports of the Velometer (15).

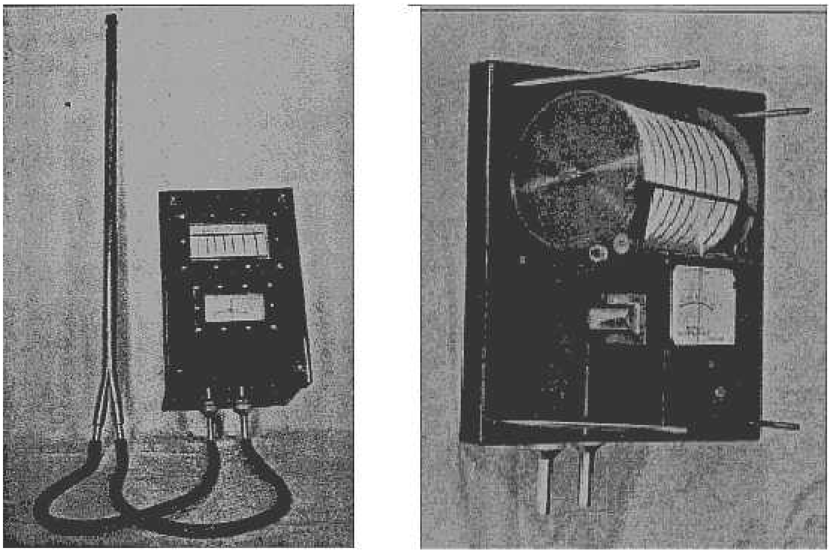

Figure 7.7 The recording Velometer
(Reproduced by kind permission of the Institution of Mining Engineers)

An instrument that appears to have been similar to the recording Velometer was the Gothe anemograph. It is shown with the case open in Figures 7.8. The apparatus was used underground at Sneyd Colliery, North Staffordshire in association with recording methanometers. The aim was to investigate how different forms of coal face ventilation affected the amounts of methane in the air stream. This work was concluded in 1959 (18).

7.4 The application of plate anemometers in coal mines

A wide variety of plate anemometers have seemingly been used in British coal mines. The reasons for this include the fact that they were frequently the only instrument available to measure the lowest wind speeds found underground. Against this was the fact that they were only suitable for use in precise, rather than the more convenient zigzag, traverses. This meant that they never became as popular as other types, notably the rotating vane anemometers to be described in the next chapter.

As to the accuracy of the results provided, there are a number of factors that suggest that this was not high. Firstly, to provide a true reading the apparatus must be set so that the 'still air' position of the sensing plate is perpendicular to the incident air current and the axis of rotation, or plane of motion, of the plate horizontal. In an inclined airway or vertical shaft it is impossible to fulfil both these requirements. Further, these anemometers usually include light vanes suspended by fine bearings. Whilst this has produced instruments sensitive to low wind speeds, they also tend to be very fragile and consequently susceptible to damage and unpredictable calibration changes in the harsh conditions found underground.

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Chapter 8 Mechanical rotating vane anemometers

When air passes a conventional horizontal axis windmill, aerodynamic forces are generated that cause the sails to rotate. Amongst other things, their resulting angular velocity is dependent upon the incident wind speed. This is the general principle behind the 'rotating vane' anemometers to be described in this chapter.

8.1 Development of the rotating vane anemometer

One of the earliest rotating vane anemometers is believed to have come about as a result of an interest Sir Christopher Wren and Sir Robert Hooke had in meteorology. Wren started his investigations at an early age, designing his first thermograph in 1647 when he was only fifteen years old. By 1663 rainfall and wind direction indicators had been added to the apparatus. At about the same time, further development of what had become a comprehensive weather recorder was taken over by Hooke. Between 1672 and 1678 he added an anemometer to the apparatus (1).

A description of Hooke's 'Weather Wiser' is included in a collection of his papers (2) published in 1726. The revolutions completed by the vanes were counted by a 'numerator'. When the number reached 100, 1000, or 10000, one of three 'punches' was operated, making a mark on a paper chart. This was moved along by clockwork. Another punch made a timing mark every quarter of an hour.

After completing his weather recorder, Hooke continued to work on anemometers. In 1683 he demonstrated a four vaned, hand held instrument. Further, he was able to show that the rate off vane rotation in a given flow could be altered by varying the angle of the blades.

In 1790, Woltmann devised a windmill type water meter (3). This instrument consisted of a two bladed vane assembly that drove a revolution counting mechanism. It is reported (4) that Woltmann suggested that it could also be used as an anemometer.

An anemometer acknowledged as being derived from the 'Woltmann Mill' was described by Charles Combes (5), the Chief Engineer of French Mines, in 1837. This had been developed for use in a series of investigations conducted in French and Belgian mines whose ventilation furnaces had been replaced by mechanical devices. A diagram of the Combes anemometer is given as Figure 8.1. The base plate was approximately 72 mm wide by 96 mm long. The number of circuits completed by the vanes was determined by counting the teeth on the gear wheels that passed the indicating pointers shown. A trigger, operated by pulling on one of two cords, allowed the rotation of the vanes to be started and stopped at will. From later descriptions it appears that sometime between 1845 and 1862 this arrangement was altered such that the counting mechanism could be disengaged from the still revolving vanes (6).

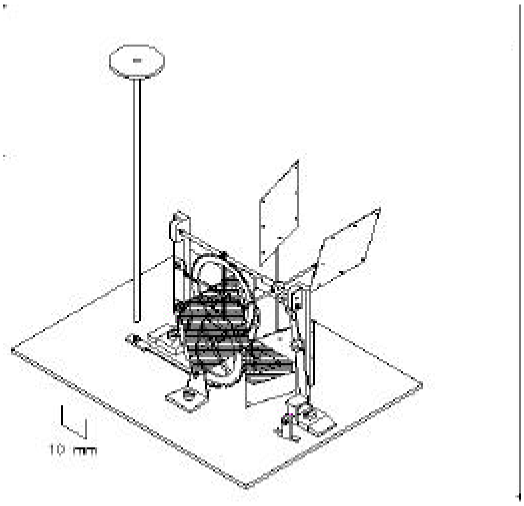

Figure 8.1 The anemometer of Combes

To use the apparatus, both the counting gears were first set to zero and the trigger engaged. The anemometer was then placed on a stand in the airway with the observer taking up position downstream and out of the flow. With the trigger released, the vanes were allowed to rotate for a measured time, preferably between two and three minutes. At the end of this period, the counting mechanism was stopped and the number of gear teeth that had passed the pointers determined. The rate of rotation of the vanes could then be calculated and an empirical formula used to give wind speed. The anemometer is reported to have been tested in flow rates from 0.4 to 5 m/s (5).

The Combes anemometer appears to have been one of the first rotating vane anemometers to be widely used in coal mines. Not only did it find application in France and Belgium, but also in Britain. However, by 1862 it was being replaced by other devices that were considered to be more reliable.

Possibly one of the earliest British mining rotating vane anemometers was constructed in 1835 by Thomas Elliot, an overman at Pensher Colliery in Durham. This consisted of a four bladed vane assembly that drove two pointers, similar to the hands of a clock, over a pair of concentric scales. These were marked to show the number of revolutions completed. A case, fitted with a carrying ring on its top, enclosed the gears of the indicating mechanism. The instrument was provided with a calibration table that enabled the wind speed to be determined from the rate at which the pointers moved over the scales (7). Whilst it met with strong approval from the Newcastle coal owners, who awarded him ten guineas for its invention, it appears that only one Elliot anemometer was ever made. Despite this it will be clear from the remainder of this section that it had a significant influence on the design of subsequent rotating vane instruments, possibly more than that of Combes.

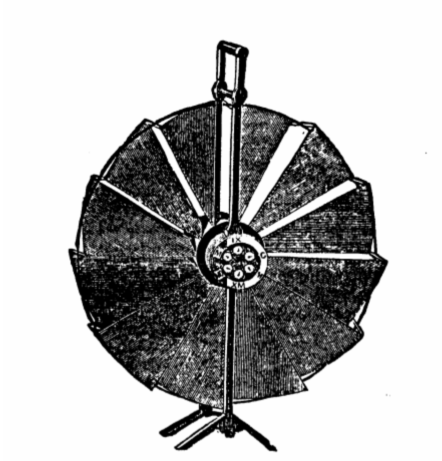

Figure 8.2 Biram's patent 12 inch anemometer
(Reproduced by kind permission of the Colliery Guardian)

In 1842, Benjamin Biram, the superintendent of the Earl Fitzwilliam's collieries, was granted a patent (8) entitled 'Rotary Engines'. This covered 'improvements giving a better form and position to the vanes and floats of those rotary machines that are moved by currents of wind, or water, or some other fluid, acting upon, or against such vanes or floats'. One of the applications envisaged for the form of vane assembly described was in a horizontal axis anemometer. In pursuance of this idea, late in 1844 Biram approached John Davis, an instrument maker from Derby, with a request that he consider manufacturing such a device for use in mines and buildings. In February 1845 Davis announced that 'Biram's Patent Anemometer', an illustration of which is given as Figure 8.2, would be ready in a few weeks (9). On these early instruments the vanes were made from oiled silk stretched on brass frames. The rotation was transmitted via gears to pointers that moved over a series of graduated scales included on the axial boss.

A significant feature of Biram's anemometer was the fact that the vane blades were each made from a truncated sector of a circle, formed such that when they were mounted on an axle their depth along the direction of flow was constant with radius. This was achieved by varying the inclination of each to the axis of rotation. By setting this helix angle at any point to be equivalent to that of a 2 ft (610 mm) pitch screw thread, it was intended that as a 12 inch (305 mm) diameter by 2 inch (50.8 mm) long cylinder of air moved through the assembly it would rotate the vanes through 1/12 of a complete circle. Thus to produce a complete circuit it was necessary for a 2 ft long column to pass. Provided all the bearings were 'friction free', Biram argued, that with such a design the incident wind speed in feet per unit time could simply be determined by multiplying the measured rate of vane rotation by two (10). Using a similar reasoning, Biram also said that the number of revolutions completed by the vanes of his anemometer would show how far the air had moved in a measured time. As an apparent consequence, its registering dials were marked in units of distance, usually feet.

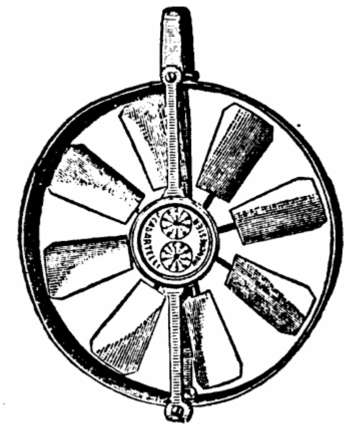

Figure 8.3 The Casartelli anemometer

Before the end of 1854, 4 inch (102 mm) and 6 inch (152 mm) diameter Biram anemometers had been introduced, with a 2 inch (51 mm) diameter instrument appearing later. With each the vanes were shaped in the same way as the older 12 inch example, but with brass sheet replacing the silk.

Sometime in the early 1870's, the design of vane anemometers was altered to include a circumferential band of metal around the vane assembly. This provided protection for the instrument and acted as a support frame. At about the same time the large twisted vanes were replaced by fixed inclination plates made of brass or aluminium. They were riveted to a 'spider' mounted on an axle between two bearings. An illustration of this form of Biram anemometer, probably first introduced by Casartelli of Manchester, is shown in Figure 8.3.

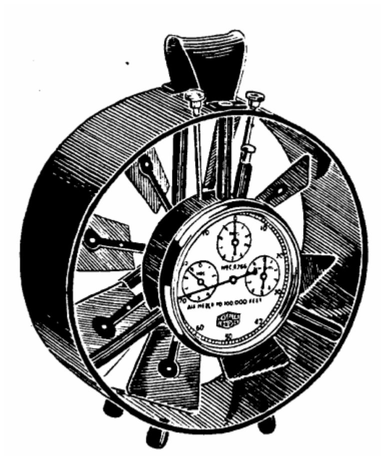

Figure 8.4 The Casella 4 inch Biram anemometer
(Reproduced by kind permission of Casella London Limited)

A 4 inch (102 mm) 'Biram' anemometer of the type used in coal mines up to at least the late 1980's is shown in Figure 8.4. This instrument was used for measuring speeds in the range 160 to 3150 ft/min (0.8 to 16 m/s) (11). Manufacturers of anemometers similar to this one have been: Casella, Short and Mason, Airflow Developments and Davis of Derby.

Another form of rotating vane anemometer that has found widespread use in coal mines is the 'Air Meter' shown in Figure 8.5. An instrument of this type was originally designed, probably by L. Casella of London around about 1870, for a Dr Parkes. He was interested in determining the state of the ventilation in the Royal Victoria Hospital at Netley, near Southampton (12). By 1875, it was being reported (13) that the anemometer was being 'much used by mine managers'. Instruments of this type have been made for use in wind speeds from 0.27 up to 50 m/s (11).

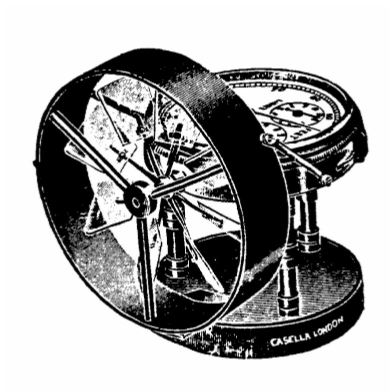

Figure 8.5 The Casella Air Meter
(Reproduced by kind permission of Casella London Limited)

For all the above anemometers, the wind speed is determined by dividing the total number of vane rotations completed, or some representation of it, by the observation time. The latter is usually measured using a stopwatch. However, in 1884, John Davis introduced a 'self timing' anemometer. This removed any need for separate time measurement and the performance of calculations. Outwardly it looked similar to a standard Biram, but as the vanes rotated they wound a spring up until its tension balanced the force of the wind. At this point the wind speed could be read directly off a dial (14). Although advertisements for the self timing anemometer were issued, it is not clear how widespread its use in mines was.

According to (15) nineteenth century Biram anemometers required a minimum wind speed of between 30 and 50 ft/min (0.15 and 0.25 m/s) before the vanes started to rotate. Others, for example (16), gave a higher threshold, in the region of 100 ft/min (0.5 m/s). In 1863 Mackworth (17) commented that this sort of performance would limit the number of places underground where the current would be strong enough to turn the vanes. Subsequent attempts at reducing this threshold have included lightening the rotating components. Since about 1890, this has typically involved making them from thin sheets of mica.

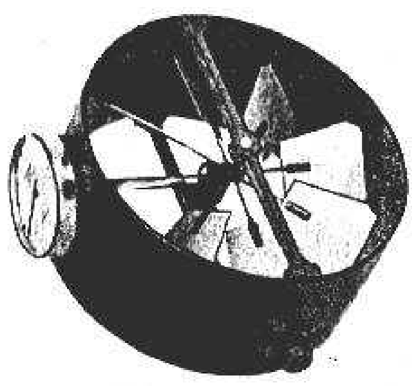

Figure 8.6 The Ower low speed anemometer
(Reproduced by kind permission of the University of Newcastle upon Tyne)

A ‘low speed’ anemometer was described in 1926 by E. Ower (18). Shown in Figure 8.6, this was intended for use in wind speeds down to about 0.15 m/s. This low speed performance was achieved by including, for example, a revolution counter consisting of a single pointer. By the late 1960’s the NCB owned around 250 Ower anemometers. Some were manufactured by Short and Mason and others by Davis of Derby.

Lowne Instruments Limited have also produced a ‘low speed’ anemometer that has found use in coal mines, although it was perhaps not as popular as the Ower. This is shown in Figure 8.7. The vane assembly, which was 45 mm in diameter, had mica vanes. This enabled the anemometer to respond to wind speeds as low as 0.2 m/s. During its development, a prototype instrument was evaluated by the NCB and advice given to its designer. Tests were carried out in a surface wind tunnel at the South Yorkshire Area and underground in either the Barnsley, or Doncaster Areas.

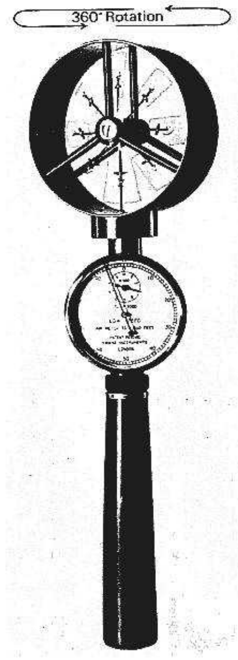

Figure 8.7 The Lowne R.H.2 low speed anemometer
(Reproduced by kind permission of Lowne Instruments Limited)

It has already been noted how Combes had, by 1862, fitted his anemometers with a clutch mechanism that disengaged the counting wheels from the vanes. By the middle of the 1870’s a similar arrangement was being included on both Biram anemometers and Parkes Air Meters. A button that could be used to reset the registering pointers to zero at the start of each test was introduced by R. M. Lowne (19), probably between 1880 and 1890. The modern Biram shown in Figure 8.4 is fitted with both start/stop levers and a zero reset button.

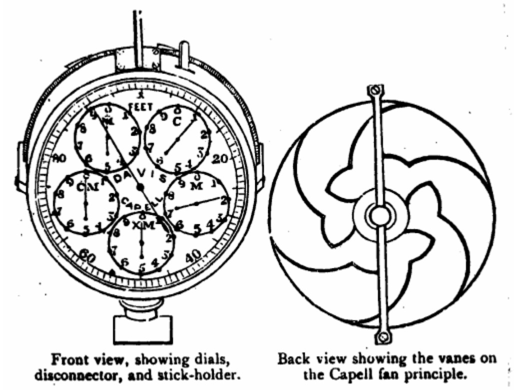

Figure 8.8 The Capell-Davis high speed anemometer

In the event of an anemometer being used in too high a wind speed, the potential exists for the vane assembly to be permanently damaged. Since very high flows can exist, for example at the intake and discharges of fans, a number of ‘high speed’ instruments have been developed.

One of the earliest of these was the Capell-Davis anemometer, developed sometime before 1898 and shown in Figure 8.8. It appears that the instrument was constructed on similar lines to a mine ventilating fan developed by the Reverend G. M. Capell, of Pembroke College, Oxford. This ventilating fan was of the centrifugal type, whereby air entering at the fan axle was ejected around its perimeter. The Capell-Davis anemometer was for use in wind speeds over 1800 ft/min (9.1 m/s) (20) (21).

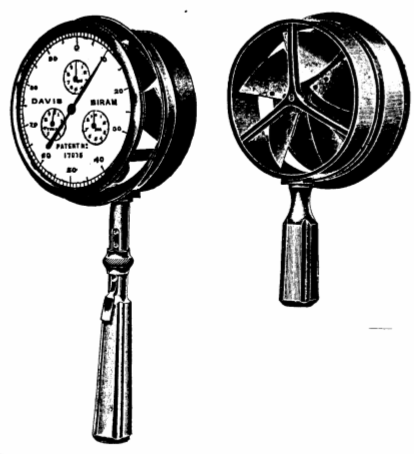

Figure 8.9 The Davis-Biram anemometer

The Davis-Biram anemometer of about 1910, shown in Figure 8.9, seems to have been a development of the Capell-Davis device. It was intended for use both in high and low wind speeds. Its peculiar shape was designed to limit the effects on the reading of an observer standing down wind of the instrument (22).

There have been few new designs of mechanical rotating vane anemometer introduced in the last thirty years. One exception is the Airflow Developments AM 5000, shown in Figure 8.10. Dating from 1968, it incorporated a mechanical digital distance indicator that could be started, stopped and reset at the press of a button. The vane assembly was made from a single sheet of stainless steel and mounted on a cantilevered axle. A boss formed at the centre of the vanes was intended to protect the bearings from the ingress of dust. The whole instrument was surrounded by a stainless steel band that allowed the anemometer, the manufacturers claimed in their sales literature, to be laid flat on the ground without damaging the vanes (23). The apparatus could be used to measure wind speeds from 1 to 25 m/s, and was considered as a 'high/medium speed' anemometer. The AM 5000 is no longer available.

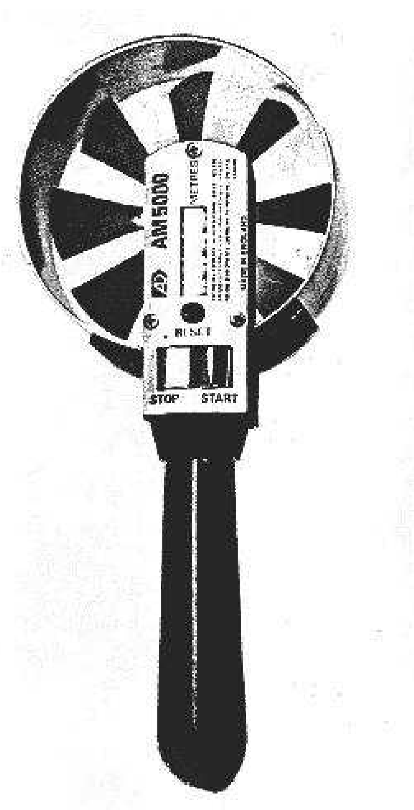

Figure 8.10 The Airflow Developments AM5000

8.2 Rotating vane anemometers used within the British coal mining industry

Until the nationalisation of the coal mining industry in 1947 each mine was responsible for the purchase and maintenance of its own anemometers. As a result, in the region of thirty different types of rotating vane instrument were in use underground at this time. When the NCB introduced centralised repair and recalibration facilities during the 1960's, it was found that this necessitated the holding of a vast stock of different spares (24). To rationalise this situation, in about 1965 an internal working party recommended that only six types of hand held rotating vane anemometer be used in British coal mines. These were to be:

Davis of Derby 'Four inch' Low Speed,

Ower 'Four inch' Low Speed,

Short and Mason 'Four inch' Medium Speed,

Davis of Derby 'Four inch' Medium Speed,

Davis of Derby 'Three inch' Medium Speed,

Davis of Derby 'Three inch' High Speed.

The four inch medium speed instruments were similar to that shown in Figure 8.4, and the Davis of Derby three inch instruments were of the type shown in Figure 8.9. The high speed version of the latter was fitted with a perforated shutter around the annulus through which the air emerged (24).

In 1966, Davis of Derby Limited ceased the manufacture of rotating vane anemometers. To avoid potentially serious repercussions as regards the supply of replacement parts for their instruments, the NCB reached an agreement whereby Short and Mason Limited took over any remaining stock of spares. These were then available for purchase by the Board as required. Unfortunately, in 1968 Short and Mason themselves ceased making rotating vane anemometers. As a consequence, the remaining stocks of spare parts for Davis of Derby instruments were sold to the NCB for internal distribution. The spares for Short and Mason anemometers went to Abbirco Limited. These were, again, available for purchase by the Board as required (24)(25).

This withdrawal of two firms from the manufacture of rotating vane anemometers in as many years, and the consequential reduction in the availability of replacement parts, forced the NCB to rationalise further on the different types of instruments used to measure air flow in mines. To this end, only makes containing interchangeable parts, or components that were readily available, were to be considered for repair. At about this time, 1968, the Airflow Developments AM 5000 shown in Figure 8.10 was introduced as a replacement for the Davis 'Three inch' medium and high speed anemometers (24).

The last published edition of NCB's Colliery Ventilation Officer's handbook (26) shows that at the end of the 1970's the anemometers used in coal mines consisted of the Airflow Developments AM 5000, the 'Biram' made by Davis, Short and Mason, and the Lowne low speed instrument. All instruments incorporated gear trains converting their indications from feet to metres. By the end of the 1980's the AM 5000 was no longer available, and both Short and Mason and Davis of Derby had long ceased making anemometers. Lowne Instruments Limited was, however, still supplying rotating vane anemometers to British Coal (27). It is suspected that during the 1990's instruments were refurbished using the parts of irreparably damaged units

8.3 The performance of vane anemometers

Before an anemometer can be used to measure air flow, the relationship between the rate of rotation of the vanes and the wind speed must be determined.

When Biram designed his anemometer he assumed that when the air moved a given distance it would produce a fixed angular rotation of the vane assembly. This led to the belief that the instrument calibration factor could be determined purely from the geometry of the system.

Combes, on the other hand, said that the 'true' wind speed (v) was related to the rate of rotation (n) of the vanes of his anemometer via:

$$v = a + bn \qquad 8.1$$

'a' and 'b' were experimentally determined coefficients. Their values were dependent upon the geometry of the system, the density of the air and the friction of the bearings in the instrument (5).

In 1861 Atkinson and Dalglish published the results (15) to an investigation into the performance of a range of rotating vane anemometers. They found that the wind speed could be calculated from the reading of a Biram by using a formula similar to 8.1, but with 'n' representing the 'indicated wind speed'. This was calculated by dividing the distance moved by the air, as shown on the instrument dials, by the observation time. Coefficients 'a' and 'b' were found to remain constant with wind speed, but varied with the condition of the anemometer and the calibration apparatus used. This latter point will be considered in Chapter 14.

In 1846 Phillips (28) published a theory for the calibration of vane anemometers in which he argued for a non-linear expression. Later, in 1898-99, Rateau (29) proposed the use of:

$$v = a + bn + \frac{c}{v} \qquad 8.2$$

From the relative values of 'a', 'b' and 'c' it is possible to show that any deviations from a straight line relationship occur only at the lower end of an anemometer's operating range of wind speeds.

By 1876 it had become usual for anemometer manufacturers to supply a correction table or chart with each instrument sold. This showed the difference between the 'indicated' and 'true' wind speeds. The figures presented were determined experimentally. By providing them, the need for the user to solve what were becoming increasingly complex equations was removed, making the task of measuring air flow using a rotating vane anemometer very much easier.

Despite the obvious advantages associated with the use of calibration charts supplied by manufacturers, there was always a suspicion that not all anemometers were individually calibrated. Swirles (30) stated that some firms were thought to send out the same chart with all instruments of a similar type. His experiments had shown that if this were the case, then inaccuracies would be introduced into the instrument reading. Such a charge had been largely substantiated by Mr Davis of Derby (31). He said that a single lithograph curve was sent out with each anemometer. It was, however, added that adjustments were made to ensure that each rotating vane anemometer responded the same at a wind speed of 600 ft/min (3.1 m/s). In his (Mr Davis) experience it was only necessary to use an individually calibrated anemometer when a high level of accuracy was required, such as in fan tests.

The correction chart supplied by a manufacturer is valid for a given instrument only if it has remained undamaged and is used in exactly the same conditions as those present during its calibration. These provisos can not always be complied with, particularly the last one. It is, therefore, important that the effects on the instrument performance of a variety of different flow conditions be properly understood so that the necessary corrections can be made to the final result.

Combes, in 1838, recognised the importance of air density on the anemometer reading (5). If the temperature, pressure, humidity, or composition of the air were perceptibly different from 'atmospheric air' he said that the value of 'a' in 8.1 should be altered. When Ower developed his theory for anemometers (32) he showed that changes in air density produce a series of parallel calibration curves. Further, at wind speeds around 1.5 m/s a change in air density of 5% could be neglected without giving rise to an error of greater than 1%. At 9 m/s a 32% density change could be tolerated. Ower and Pankhurst report (33) that other workers have obtained similar theoretical results for turbine type gas flow meters (a vane anemometer fitted in a pipe), and that these have been verified experimentally.

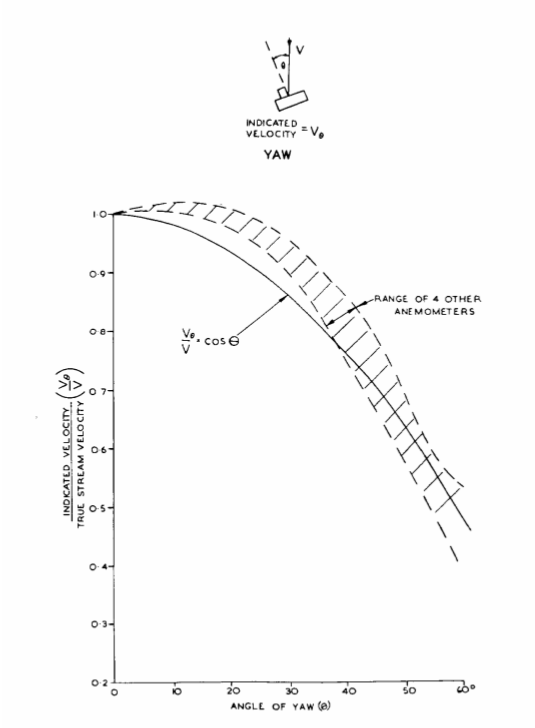

Figure 8.11 The effects of yaw on the reading of a vane anemometer (British Coal)

Anemometers are usually calibrated with their axis of rotation parallel to the wind direction. Underground, it is not always possible for the operator to align the instrument correctly in the air way, or alternatively the flow may be turbulent giving rise to an off axis component of velocity. Various workers, notably Ower (32) and Swirles and Hinsley (34), have studied the effects of 'yaw' (the angle between the anemometer axis and the flow direction) on instrument reading. A graph summarising the results from these workers is given as Figure 8.11 (35). It shows that, in general, the ratio of the wind speed after correction to the true value is equal to 1 ± 2% if the angle of yaw is less than 20^o.

As noted above, mine air flow is unsteady. Further, the appreciation that the internal components of a rotating vane anemometer possessed inertia led to the realisation at a very early date that such instruments could provide erroneous readings in such conditions.

Rateau (29) reported the results to a series of experiments in which he investigated the behaviour of a vane anemometer in pulsing flows. The instrument was mounted on a pendulum, and swung back and forth between two jets of air flowing side by side. Insufficient work was done to enable Rateau to draw any firm conclusions, but his results do show that the instrument error increases with the amplitude of the flow fluctuation.

A theoretical discussion of the measurement of pulsing flows was presented by Ower (32). He investigated the behaviour of rotating vane anemometers in a sinusoidally varying flow. It was found that the error in the reading given was proportional to the square of the amplitude of the fluctuation, expressed as a ratio of the mean velocity. Ower and Pankhurst (33) state that Ower's theory has been confirmed by experiment using a turbine gas flow meter. It is also stated that some workers have indicated that additional allowances may be necessary if the wave shape deviates from the sinusoid.

Teale (35) attempted to verify Ower's theory for pulsing flow by moving an anemometer backwards and forwards along the axis of a duct connected to a forcing ventilation system. The results, presented in Figure 8.12, show errors less than those predicted.

Experiments in a surface test gallery, conducted using a hot wire anemometer, revealed (35) the existence of flow pulsations with amplitudes up to 100% of the mean speed. From Figure 8.12 it will be seen that under these conditions a vane anemometer could be expected to provide a wind speed indication up to 30% too high. Although large, it is not clear whether an error of this magnitude is likely to be significant in mine ventilation work.

Ower and Pankhurst (33) have indicated that in pulsing flows there is a possibility that the error in the reading of a rotating vane anemometer can only be predicted if the pulsations are sinusoidal. Teale (35) stated that the fluctuations in flow he observed in his test gallery were of an unpredictable size and form. Taking these two comments together it can be concluded that the absolute accuracy of a vane anemometer reading is likely to be unpredictable when the measurement is of mine air flow.

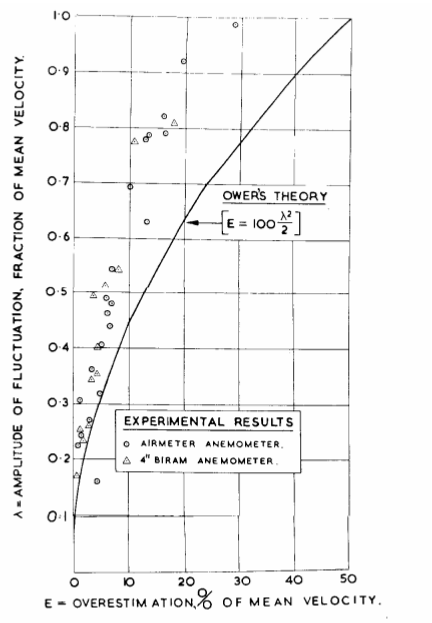

Figure 8.12 The error of vane anemometers in fluctuating air streams (British Coal)

8.4 Reliability of vane anemometers in coal mines

In normal use underground in a coal mine a rotating vane anemometer may be damaged such that it either becomes completely unusable or has its calibration factor changed by an amount that is possibly significant and yet undetectable to the user on site. To guard against the latter eventuality it is important that each anemometer be serviced in a laboratory at regular intervals.

Following a survey of the condition of 400 vane anemometers received at an NCB repair facility, Jackson reported (36) that 46% of them required some repairs and that 49 % of these had unspecified bearing related faults. Damage to the vane assembly was invariably caused, Jackson stated, by instruments being used outside their designed range of wind speeds. The mechanical reliability of the start/stop and zero reset mechanisms also gave some cause for concern, and in fact Browning (37) says that most Colliery Ventilation Officers were told not to use these facilities because of problems associated with them.

8.5 Concluding remarks

Rotating vane anemometers have been used to measure air flow in coal mines for over a century, and still exist in a form similar to that introduced in the 1870's. Those in use in the late 1980's would have been familiar to a mining engineer of a century earlier. There are many reasons for this longevity, for example: the instrument is easy to use, it gives an on the spot reading of air flow, and it can be used to any part of a mine without the need for other services, such as electricity. There are, however, problems associated with the use of this type of instrument in a coal mine. The effects of dust have been generally accepted as a fact of life. The unpredictable performance of vane anemometers in the pulsing mine air flow has, on the other hand, been largely ignored.

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Chapter 9 Electrically sensed rotating vane anemometers

This chapter describes the development of anemometers in which the rotation of the vane assembly is sensed electrically. The development by the NCB of fixed, remote indicating anemometers is considered separately in the next chapter.

The earliest electrical anemometers used the rotation of the vane assembly to periodically open and close a switch. This was connected in a circuit containing a battery and an indicating mechanism, often an electromagnet. As the vanes rotated this was caused to pulse, enabling the number completed in a measured time to be determined. A conversion table or formula was used to give the corresponding incident wind speed.

One of the earliest instruments of this type was described by Angelo Secci in 1858-9. The apparatus was designed for meteorological use (1).

In 1877-8 Henry Hall drew up a proposal (2) for a system of electrical air flow monitors for coal mines. The flow sensor to be used was a Biram anemometer. This was arranged such that on the completion of every ten revolutions a spring, forming part of a permanent magnet, was caused to vibrate. A coil was wound around this magnet and connected to a telephone receiver on the surface. Thus when the spring vibrated a voltage was generated in this coil producing, in turn, an audible signal in the receiver. An observer wishing to know the wind speed at a particular site only had to count the number of pulses he heard and perform the calculation described above. Reference (3) to a 'Hall ventilation recorder' in use at Park Colliery, possibly near Wigan, may be evidence that this apparatus was used in coal mines.

Another nineteenth century remote indicating anemometer developed for coal mines was described by Bagot (4), in 1882. Very little information is given about the instrument, but it does appear that the flow sensor was based on the vertical axis cup anemometer developed by Robinson and usually associated with meteorological applications. Bagot's apparatus was to be placed at the extremities of the mine with wires connecting an electrical rate of rotation sensing device to a chart recorder in the fan engine house.

Probably one of the earliest direct reading electronic vane anemometers (one that shows the flow rate on a meter calibrated in units of wind speed) was described by Marsden (5) in 1948. In this apparatus the rotation of the vanes periodically interrupted a light beam that was allowed to impinge on a photocell. The pulsing output from this was processed to produce a dc analogue of the input wind speed. This could be displayed on a meter or a recorder. The apparatus was constructed using thermionic valves and was thus unlikely to be suitable for use underground in coal mines.

A portable, transistorised, optically sensed rotating vane anemometer was produced by Short and Mason Limited in about 1958 (6). The Scottish Area of the NCB subsequently conducted laboratory tests on a similar instrument with the intention of using it in their anemometer calibration facility (7). However, light sensed instruments do not appear to have been widely used underground in coal mines. One possible reason for this is that accumulations of dust on the light transmitting surfaces can lead to failure of the device.

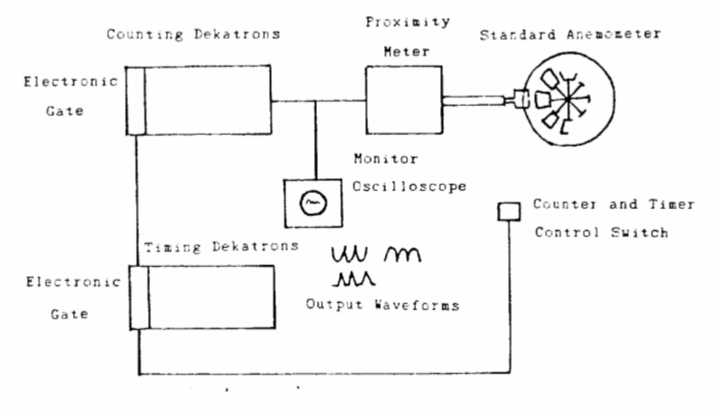

Figure 9.1 Higgins's capacitively sensed rotating vane anemometer (British Coal)

An alternative non-contacting method of detecting the rotation of an anemometer's vanes was described by Higgins (8) in 1957. He positioned two wires separated by a small air gap close to the perimeter of their circle, as shown schematically in Figure 9.1. As each blade passed the gap, the capacitance of the system changed. This fact was detected by a 'proximity meter'. When the vanes were rotating freely under the influence of the air current the output from the meter consisted of a series of pulses. These were counted automatically and the result periodically displayed. The apparatus was used in the NCB's Scottish Laboratory to provide an automatic indication of the rate of rotation of a 'standard' Biram anemometer during the re-calibration of repaired instruments. It is not believed to have been used underground.

In 1962 a patent (9) was published on behalf of Gurry and McCarthy describing electrical apparatus to sense a change in capacity between a probe and earth. The device consisted of a 1 MHz (typical) oscillator that was used to alternately charge and discharged the capacitance under test. During the charge cycle, a voltage was developed at the device's output terminal. Its size depended upon the capacitance of the probe. During the discharge cycle the output was zero. If the sensor was mounted in close proximity to, for example, a rotating shaft with a raised stud fixed to it, the output voltage was a high frequency ac signal, whose amplitude showed a series of lower frequency peaks corresponding to the shaft's rate of rotation. It was important that the oscillator frequency was very much higher than the frequency of the change in capacity that was to be monitored. Manufacture of the sensor was undertaken by Grunther Industrial Developments Limited (GID), who marketed it as their CT series transducers. The apparatus was sold as a small encapsulated block, about 25 mm cube. This contained the transistorised oscillator and an output circuit.

Figure 9.2 The RM 137 direct reading electronic vane anemometer (British Coal)

Even before the patent for the capacitance transducer had been granted, Short and Mason and GID had collaborated in its use in the RM 104 and RM 137 direct reading electronic vane anemometers. A photograph of the latter device, incorporating a '4 inch' vane assembly, is reproduced as Figure 9.2. The probe was mounted close to the perimeter of the vane circle. As the anemometer rotated an oscillating output signal was generated by the transducer. Its frequency was related to the wind speed past the detector head. An indicator unit converted the ac signal into a dc current for display on a meter calibrated in feet per minute. A switch allowed its span to be set to one of three values: 0 to 200 ft/min (1 m/s), 0 to 1000 ft/min (5 m/s) and 0 to 5000 ft/min (25 m/s). The stated accuracy of the instrument was +/- 2%. Internal rechargeable cells provided the power, giving a life of about twenty hours continuous use. A clockwork driven chart recorder, shown at the left of the photograph, could be connected to the apparatus to display trends in air flow (10)(11). The RM 137 was used by MRE both in investigations of air flow patterns underground and as the basis of their Type 813 recording anemometer to be described in Chapter 10.

In 1968, Short and Mason Limited ceased manufacturing anemometers and further developments in this field passed to the firms of Abbirco and Airflow Developments Limited.

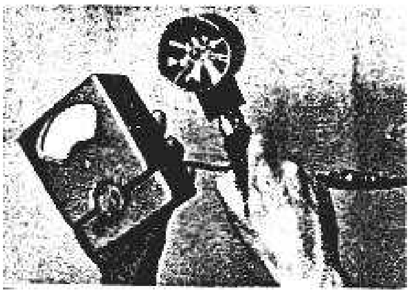

Figure 9.3 The Abbirco Flowmaster
(Reproduced by kind permission of the Colliery Guardian)

Abbirco Limited used a Grunther capacitance transducer in their Flowmaster electronic rotating vane anemometer shown in Figure 9.3. It was first manufactured in about 1970. The instrument was similar in its concept to Short and Mason’s RM 137, but was considerably smaller. This made it a truly ‘hand held’ anemometer. Fitted with a 70 mm diameter vane assembly, the bearings were shrouded to limit the possibility of their becoming contaminated by dust. A control unit included a PP3 size dry battery power supply and a meter to display the wind speed. A switch allowed its span to be selected from one of three wind speed values: 0 to 1.5 m/s, 0 to 5 m/s, or 0 to 15 m/s. The accuracy of the reading was given as +/-2%.

Figure 9.4 The Airflow Developments LCA 6000 (VT) anemometer
(Reproduced by kind permission of Airflow

Some Abbirco Flowmaster instruments were modified and certified as intrinsically safe for use in coal mines (see Appendix II). However, their inability to average the flow over a long period of time, such as is required in a zigzag traverse, tended to limit their use to special investigations.

More recently Airflow Developments Limited have produced the LC 6000 and the LCA 6000 (VT) hand held rotating vane anemometers. The LCA 6000 (VT) is shown in Figure 9.4. Operating over a range from 0.2 to 30 m/s, it is capable of providing an indication on a digital liquid crystal display of the flow rate averaged over either 3 seconds or any period up to 2 minutes. This would make the apparatus suitable, in principle, for general underground air flow measurements. It has not been ascertained whether the LCA 6000 has been certified intrinsically safe for use in a coal mine. However, it does appear to have been tested by British Coal on an experimental basis (12). No results to these trials have been located.

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Chapter 10 Electronic anemometers developed by or at the request of the NCB

Up to the late 1950's the anemometers used to monitor the ventilation in British coal mines were, in general, the same as those in use at the turn of the century. Few, if any, had remote indication or recording facilities. Consequently, mine managers had to rely on periodic ventilation surveys for information regarding the conditions underground. This situation was changed when the NCB's Mining Research Establishment started work on a series of environmental monitors specifically for use in coal mines. The work was continued at the Mining Research and Development Establishment and resulted in the production, in association with outside organisations, of a comprehensive range of ventilation monitoring equipment.

This chapter describes the systems developed during this period. Much of the information used in its compilation was gathered from the personal notes of the people involved with the projects.

10.1 The MRE recording anemometer Type 813

The first MRE recording anemometer arose from a program of work designed to investigate the aerodynamic resistance of mechanised coal faces. This necessitated the collection of continuous recordings of air pressure and flow. When the project was started, no suitable systems were available and so measurements were made using hand held instruments.

In 1963 MRE began negotiating with Short and Mason and Grunther Industrial Developments with a view to their submitting the RM 137 direct reading anemometer for certification as intrinsically safe for use in coal mines. However, the design of the apparatus proved unsatisfactory, partly due to the use of a wooden box as an enclosure. Consequently, it was necessary for MRE to make a number of modifications. The resulting apparatus, designated the MRE Recording Anemometer Type 813, is shown in Figures 10.1 and 10.2. It was certified as intrinsically safe in 1967 (1).

The Type 813 recording anemometer consisted of a sensing head, an indicator unit and a recorder. When installed underground, the complete system was enclosed in a protective steel mesh cage.

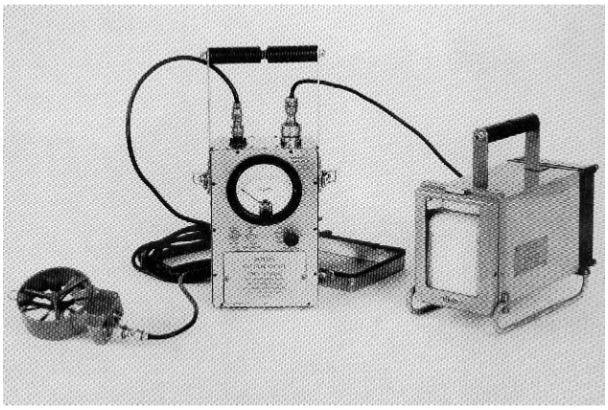


Figure 10.1 The components of the MRE Type 813 recording anemometer (British Coal)

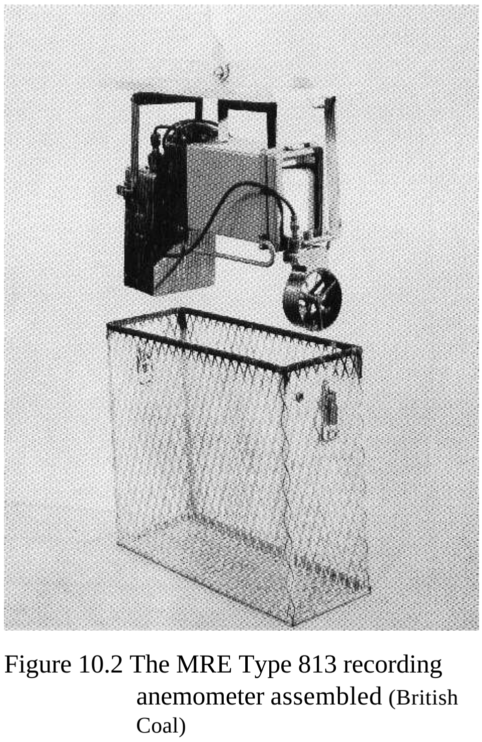


Figure 10.2 The MRE Type 813 recording anemometer assembled (British Coal)

The sensing head incorporated a Short and Mason '4 inch' vane assembly fitted with a GID capacitance transducer. At the indicator unit, its output was converted into a dc current for display on a meter calibrated directly in units of wind speed. It could also be fed to a clockwork driven 'Record' pen recorder. The full range output from the instrument could be made to correspond to one three values by operating a switch on the indicator unit. These were: 0 to 200 ft/min (0 to 1 m/s), 0 to 500 ft/min (0 to 2.5

m/s) and 0 to 2000 ft/min (0 to 10.2 m/s). To damp out any rapid fluctuations in the air flow reading, a time constant could be switched into the meter and recorder circuits. The system was powered by two internal PP9 dry cells, giving about 100 hours continuous use (2).

In all, a total of twenty four Type 813 units were supplied to the NCB. Some were made by Airflow Developments when Short and Mason withdrew from the manufacture of anemometers.

On installation, it was recommended (3) that the Type 813 be positioned half way along a straight stretch of uniform roadway at least 100 m long. The detector head was to be mounted one sixth of the roadway diameter from the wall. Once in place, the position factor (mean roadway velocity divided by the instrument reading) was determined using a zigzag traverse. When necessary, a camel-hair brush could be used to remove accumulations of dust from the vanes. It was suggested that every six months the system be removed from the mine and returned to the laboratory for a complete overhaul and re-calibration.

Following its certification, Type 813 recording anemometers were installed at a number of collieries. This use highlighted the existence of a number of problems associated with the system. One of these was associated with the recorder used. In damp conditions the paper jammed in the chart drive mechanism (1). As a result, alterations were made to its design. Despite these initial ‘teething troubles’, the system was used to investigate the behaviour of permanently installed anemometers in coal mines and in other mine ventilation studies.

10.2 The early development of NCB remote indicating anemometers

One of the features absent from the above system was the ability to provide an indication of air flow at a location remote from the measuring point. Indicating anemometers that could do this were developed by MRE as part of a project to produce a range of permanently installed environmental monitors. These were intended to provide the manager with up to date information on the atmospheric conditions in all parts of his mine.

In 1966 a requirement specification (4) was issued for a mine air flow indicator. The apparatus was to include the Short and Mason/GID flow sensor used in the Type 813 and have a full range signal output in the range 0 to 2.0 Volts dc. No local indication of flow was required. Apparatus built to this specification was to be designated the ‘NCB/MRE Airflow Transducer Type 814’. However, late in 1967 the specification was revised changing the output range to 0.4 to 2.0 Volts dc. The idea was that whilst an output of 0.4 Volts would indicate zero wind speed and 2.0 Volts full range, any fault in the apparatus would cause it to rise above 2.0 Volts, or fall below 0.4 Volts. Switching the apparatus off also caused the output to fall to zero. Instruments made to this specification were to be designated Airflow Transducer Type 815 (4). Outwardly, there were no differences between the Type 814 and 815 systems. One or other of these is shown in Figure 10.3.

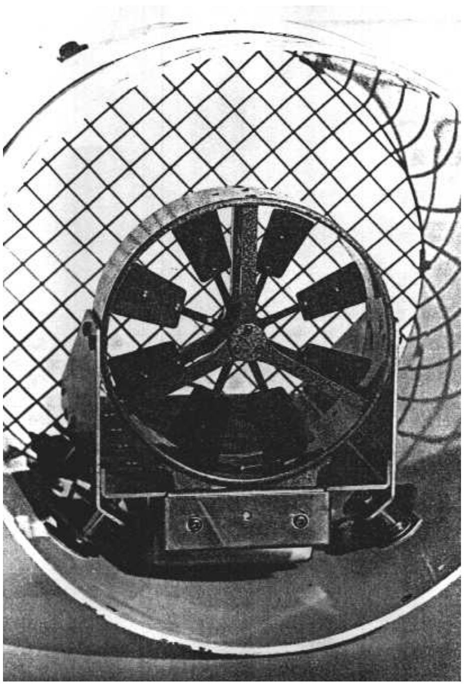


Figure 10.3 The MRE Type 814/815 air flow monitor (British Coal)

Development of the new instruments was undertaken by Dynamco Limited. In 1968, permission was obtained to install a prototype instrument underground at Bevercotes Colliery in Nottinghamshire on an experimental basis. Subsequent application for certification of the Type 815 air flow monitor as intrinsically safe was rejected on the grounds that no suitable power supply was available. Consequently, modifications were made to the system and its designation changed to Air Flow Transducer MRD 54140. This was certified as intrinsically safe for use underground in coal mines in 1971/2 (5).

Thirteen MRD 54140 systems were ordered. The first was installed underground late in 1972. One placed underground at Daw Mill Colliery in Warwickshire lasted only a few weeks before it 'failed'. Similar experiences at other sites led to a cessation of the underground trials until a solution to this apparent unreliability had been found. Eventually it was discovered that small specks of dust were altering the value of a trimming capacitor in the vane rotation sensing circuit (6).

In 1970 a working group was formed at MRDE to draw up specifications and guidelines for a series of new environmental monitoring instruments. These were to be built in a modular form, each comprising a detector head and control unit. They were all to be operated from a series of NCB standard power supplies. The output, which was to be in the range 0.4 to 2.0 Volts dc, was to be displayed locally on a meter and, if required, a standard underground recorder. It was also to be capable of being transmitted to the surface. The specification for a 'unitised air flow monitor' was issued in 1971 (7)(8).

During the late 1950's, the West Midlands Division of the NCB became interested in finding out how different methods of mine ventilation affected the amount of methane released into the air current. This work required the use of a recording anemometer. Early trials (9) had involved the use of the Gothe anemometer shown in Figure 7.8, but both this and the MRE instruments described above were considered unsuitable for later work. Consequently, the East Wales Laboratory of the NCB decided to conduct a detailed examination of the Abbirco Type 801 detector head used in the Flowmaster instrument (10). Over a ten week period the wind speed corresponding to a given output from the system changed by less than +/- 3%. Contamination of the detector head by dust was not a problem, provided it was serviced every ten to twelve weeks. As a result, it was concluded that the Abbirco Type 801 detector head 'is capable of providing the basis of a continuous monitoring system' (11).

Partly as a result of this conclusion, it was decided that the new MRDE unitised air flow monitor developed to the 1971 specification would incorporate the Type 801 flow sensor. The resulting apparatus, designated the BA1, was made by Abbirco Limited under contract to the NCB (6). The complete system, comprising detector head, control unit, battery power supply and recorder, is shown installed underground in Figure 10.4 (Clive Bavington of MRDE in photograph). Unlike the earlier remote indicating anemometers the apparatus was fitted with alarm facilities that were activated when the air flow fell below a pre-set level. The full range output of the apparatus, 0.4 to 2.0 volts, could be made to correspond to one of three wind speed ranges. These were: 0 to 1.0 m/s, 0 to 5.0 m/s and 0 to 10.0 m/s. Laboratory tests showed that the minimum detectable flow was 0.3 m/s (8).

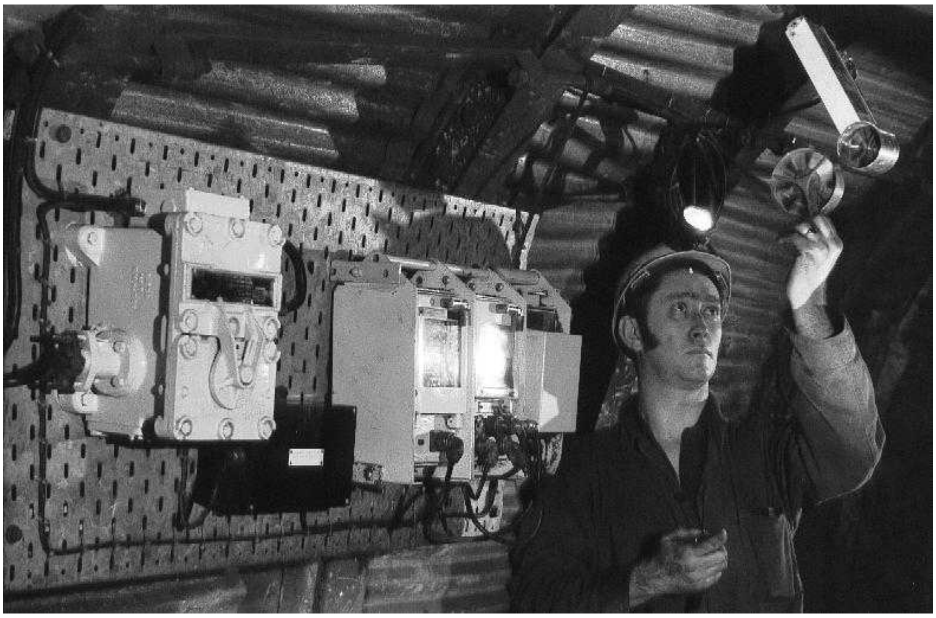


Figure 10.4 The BA1 air velocity monitoring system (British Coal)

The BA1 air flow monitor received its certificate of intrinsic safety in 1974, with the first instruments being installed underground at Daw Mill Colliery, in Warwickshire, Holditch and Hem Heath Collieries, near Stoke on Trent, and Brodsworth Colliery, near Doncaster, in the same year. After only about three weeks operation the system at Daw Mill failed. It soon became apparent that, despite the rigorous testing in the laboratory, contamination of the vane assembly bearings by dust was a major problem. One attempt at finding a solution involved the Royal Aircraft Establishment making observations of the flow of air around a number of different types of vane assembly using shadow photographic techniques. Eventually it was concluded that the main problem was associated with the relatively low driving torque produced by the small diameter Abbirco vane assembly when compared with other types (12).

10.3 The BA2 air velocity monitor and the BA3

Confirmation of the relative reliability of alternative rotating vane assemblies when operating underground in a coal mine was investigated at Daw Mill Colliery. Various forms were installed at a dusty site. They were free running without any associated electronics. Within three days the 70 mm diameter Abbirco heads had ceased rotating, whilst a 100 mm diameter Airflow Developments vane assembly, similar to that used in the AM5000 hand held anemometer, was still running some eight months later. As a result of experiences such as these, the specification for an 'NCB single headed air velocity monitoring system' was revised and the development of a new instrument, to be designated the BA2, undertaken. The first units were delivered to MRDE by Envit Limited in 1976 (8).

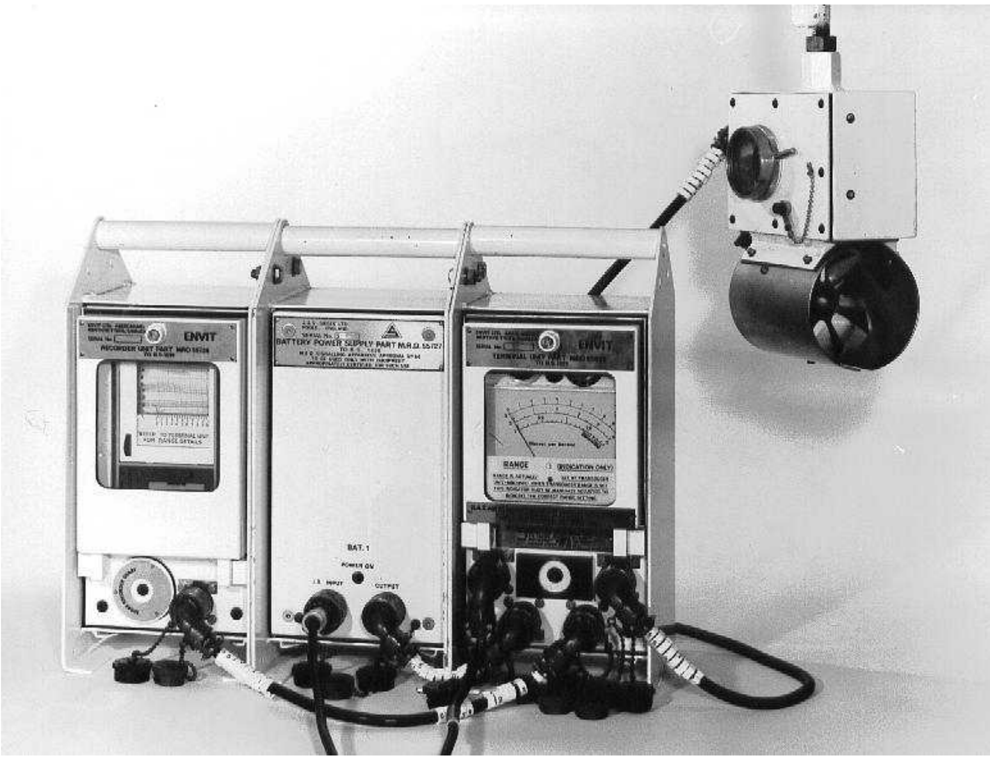


Figure 10.5 The BA2 air velocity monitoring system (British Coal)

A laboratory photograph of the BA2 air velocity monitor reproduced as Figure 10.5. Its detector head incorporated the Airflow Developments 100 mm diameter Mk II vane assembly fitted with a capacitive rotation sensor. Internal switches enabled the span of wind speeds corresponding to a change in output (from the detector head) from 0.4 to 2.0 V dc and the applied signal time constant to be changed. The three wind speed ranges that could be selected were: 0 to 2 m/s, 0 to 5 m/s and 0 to 10 m/s.

The control unit supplied power to the detector head. It also contained a meter for displaying the measured wind speed. Sockets allowing access to an electrical analogue of this were provided for the connection of local and remote indicators and recorders. In addition, the system included an internal relay that could be used to operate external alarms if the air flow fell below a set level. Under normal conditions its contacts pulsed once every 15 seconds to indicate that the system was functioning correctly. When the alarm was raised, the flash rate increased to one pulse every second. Excursions of the analogue output outside the range 0.4 to 2.2 Volts caused the 1 or 15 second flashes to be inhibited, thereby indicating a system fault. Power to the BA2 was provided by a recognised external dc source. As an example, this could be the 7 Ah Bat 1 shown in Figure 10.5. This could be float charged underground from a mains powered DC3 power supply (not shown in the photograph).

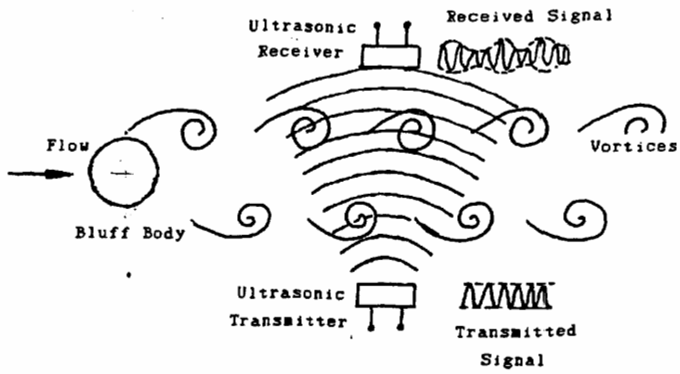
The first two BA2 air velocity monitors were installed underground at Brodsworth Colliery in 1976. Since that date many more have been used in coal mines, both by the NCB and overseas companies. Experience has shown that the reliability of the vane assembly has far surpassed the initial confidence placed in its design (13), although the positioning of the range and time constant switches in the detector head can be a bit inconvenient when the apparatus is installed near the roof of a large roadway.

Production of the BA2 ceased in 1986 due to difficulties in obtaining some of the electronic components and because of the introduction of alternative instruments described below.

In 1975, development work started on a replacement for the BA2. This instrument, designated the BA3, was also fitted with a rotating vane flow sensor. Before a prototype instrument could be completed an alternative flow sensor was found and work on the apparatus was halted.

10.4 The vortex shedding flow sensor

Figure 10.6 The operating principles of vortex shedding flow sensors



The problems associated with the use of rotating vane anemometers in dusty environments underground led MRDE to undertake a review of alternative forms of flow sensor for inclusion in a fixed anemometer. Included amongst these were those that used the phenomena of vortex shedding. As shown schematically in Figure 10.6, when air flows past a bluff body a series of swirls, or vortices, are shed from the object. These move downstream with the flow at a speed approaching that of the free stream. One manifestation of the phenomena of vortex shedding is the aeolian tones produced by a tensioned wire as it vibrates in a moving air current. In 1878, Strouhal showed that the sound frequency was proportional to the wind speed and inversely proportional to the wire's diameter. Rayleigh extended this work, introducing the non-dimensional relationship:

$$S_t = \frac{fd}{v} \qquad 10.1$$

where S_t is called the Strouhal Number, f is the frequency of vibration, v the wind speed and d the width of the wire normal to the flow (14).

In 1954, Roshko (15) reported measurements of the Strouhal Number for a rigid circular cylinder at a range of Reynolds Numbers. As a result, he was able to construct a flow meter in which the flow rate was determined from observations of the vortex shedding frequency and 10.1. This was sensed using a heated wire placed down stream of the cylinder. Subsequently, many other workers developed vortex shedding flow meters. A variety of bluff body shapes have been used in an attempt to minimise any variations of the Strouhal Number with flow rate. It will be seen from 10.1 that only if this is done will the system output frequency vary linearly with flow rate. Several different methods of sensing the vortices have also been used (14).

In 1973, the US firm of J-Tec described (16) apparatus in which the vortex shedding frequency from a circular cross section strut was monitored by directing an ultrasonic beam through the wake as shown in Figure 10.6. Each vortex constituted a disturbance in the free stream flow, scattering the ultrasound and periodically reducing the amplitude of the received signal as a consequence. The frequency of this modulation corresponded to the vortex shedding frequency and hence, via 10.1, to the wind speed past the strut, assuming that the Strouhal Number remained constant.

Initially, anemometers made by J-Tec were intended as air speed indicators for aircraft, operating over a wind speed range from 2 to 160 knots (1.0 to 82 m/s). By 1974 more sensitive ‘draft sensors’ were being made for use in coal mines.

Between 1976 and 1978, MRDE conducted an investigation into the possible use of the J-Tec vortex shedding anemometer in British coal mines. It was found that the instrument itself was not suitable for immediate use, mainly because it required a non-NCB standard power supply and had an inadequate range of operation. However, it was recommended (17) that in view of the overall performance recorded and its apparent insensitivity to mechanical damage and accumulations of dust that the NCB consider the development of its own vortex shedding anemometer.

10.5 The BA4 and BA4 Mk II air velocity monitors

Commercial development of a vortex shedding anemometer system for use in British coal mines, designed to an NCB specification was undertaken by M.S.A. (Britain) Limited in association with MRDE. The flow sensor to be used was developed by Technitron Limited. Designated the BA4 air velocity monitor, it is shown in Figure 10.7. As with the earlier NCB unitised anemometers, the system consisted of a detector head, a control unit, a power supply and an optional recorder unit.

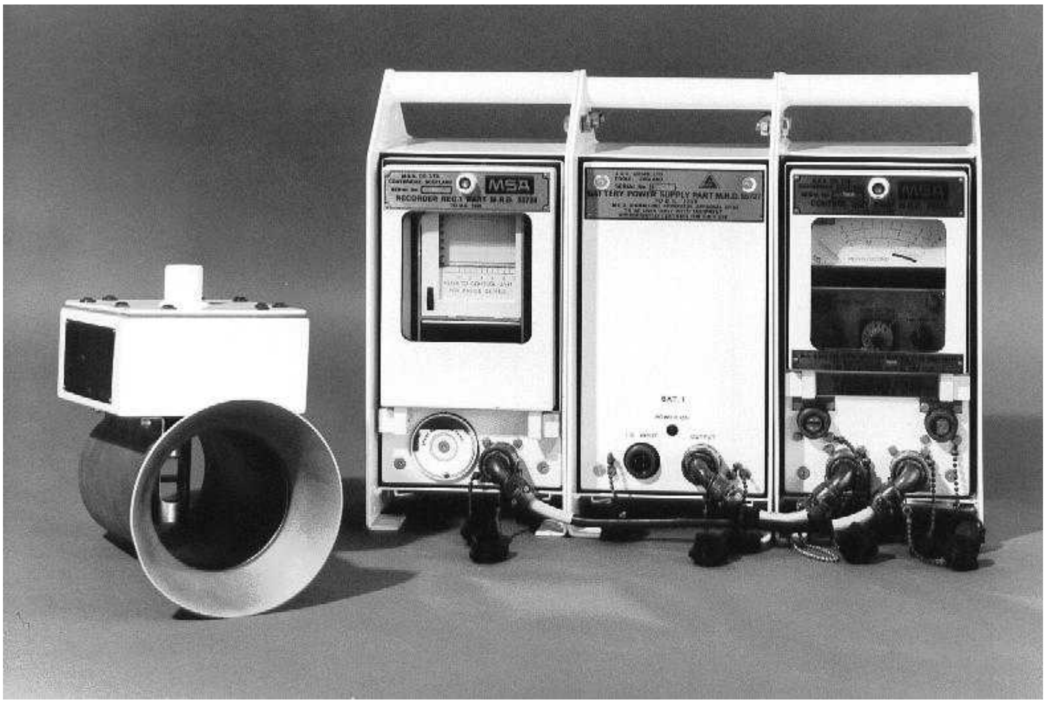


Figure 10.7 The BA4 air velocity monitoring system (British Coal)

Inside the detector head, the vortices shed by a small triangular strut modulated the amplitude of a 150 kHz ultrasonic beam. The detected signal was then processed to produce a dc voltage output in the range 0.4 to 2.0 V. This was an analogue of the shedding frequency, and hence the sensed wind speed.

The control unit contained a meter, alarm circuits and sockets that enabled the system to be used with remote indicators, as described for the BA2. Unlike this instrument, however, the range change and time constant switches were at the control unit instead of being in the detector head. Three ranges of wind speed could be selected for display. These were: 0 to 2 m/s, 0 to 5 m/s and 0 to 10 m/s.

A certificate of intrinsic safety was granted to the BA4 system in February 1979. By the end of 1981, over one hundred instruments had been supplied to the NCB (18).

Experience with the use of the BA4 underground showed it to be less sensitive to mechanical damage than rotating vane instruments. It was found, however, that accumulations of dust could lead to erroneous wind speed indications. This problem was easily rectified on site without disturbing the instrument’s calibration by removing the deposits with a brush.

After its introduction, MRDE was asked to investigate the possibility of extending the maximum working range of the BA4 from 10 to 20 m/s. A series of laboratory tests showed that some detector heads gave a linear output at the higher flow rates, whilst others did not. As a result of this seemingly unreliable performance, it was decided to develop a completely new vortex shedding flow sensor. This is described in the next section.

M.S.A. (Britain) Limited, on the other hand, continued to develop the BA4 and, in 1980, introduced the BA4 Mk II air velocity monitor. This was outwardly the same as the BA4 with the exception that the 0 to 5 m/s range has been removed and one spanning 0 to 25 m/s added in its place. In 1988, British Coal carried out a series of tests on the BA4 Mk II system. The results, which are not available for publication, showed that the instrument operated in flow rates over 20 m/s. However, a detailed examination revealed no major differences between the flow sensors of the BA4 and BA4 Mk II instruments that could account for this apparently improved performance.

10.6 The development of the MRDE vortex shedding anemometer detector head (19)

Following its failure to obtain a satisfactory response from the BA4 air velocity monitor in wind speeds much above 10 m/s, in 1980 MRDE began developing a new vortex shedding anemometer detector head. This was to be capable of operating reliably at wind speeds above 20 m/s in an air velocity monitoring system similar to the BA4. It was also to be suitable for use in a proposed hand held anemometer. In view of the experience gained during the development of the BA4 it was decided to continue using ultrasound to detect the vortices.

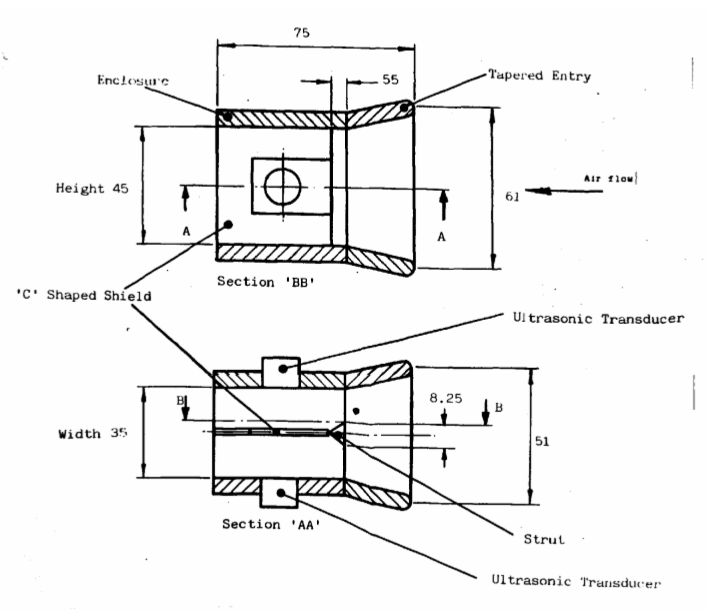


Figure 10.8 The MRDE vortex shedding air flow sensor (British Coal)

10.6.1 Design of the vortex shedding flow sensor

The design of the new MRDE vortex shedding air flow sensor, shown in Figure 10.8, commenced with an investigation into how the spacing, relative orientation, and surroundings affected the amplitude of a beam of ultrasound transmitted across an air gap. This was done in still air. A strut was then added and further tests conducted in moving air to produce a flow sensing head configuration that would reliably detect wind speeds over the maximum possible range. For this work the ultrasonic transmitter was driven by a 40 kHz oscillator. The output from the ultrasonic receiver was connected to a circuit that detected the amplitude modulation of the carrier wave.

It was found that in still air the amplitude of the received carrier wave was a maximum, and the noise on the modulation signal a minimum, when the ultrasonic transducers were coaxial and separated by a distance equal to an odd number of half wavelengths of the ultrasound. Further, when the height and depth of the enclosure forming the flow sensor was varied, a series of maxima and minima were observed in the amplitude of the detected carrier. It was deduced that the top and bottom of the enclosure were reflecting off axis ultrasound, emitted by the transmitter, on to the receiver. The detected carrier wave amplitude was a maximum when the directly transmitted and reflected signals were in phase at the receiver.

The tests in moving air showed that although the amplitude of the modulation signal varied at the vortex shedding frequency, it was also modulated at separate 'noise' frequency. This resulted in a regular, and undesirable, loss of signal. Calculations indicated that the problem was probably caused by the vortices periodically changing the phase between the off axis and direct ultrasonic beams. It was cured by fitting the 'C' shaped shield in the flow sensor enclosure as shown in Figure 10.8. This prevented any radiation reflected of the enclosure walls from reaching the ultrasonic receiver. Also, it prevented vortices downstream of the direct ultrasonic beam from scattering radiation back towards the receiver. This was believed to be a source of the 'noise' modulation at the higher wind speeds.

Further improvements in system detector performance were achieved by fitting the tapered entry shown in Figure 10.8. This made the system more sensitive to low speed and less prone to errors when miss-aligned with the air flow.

Early tests with the MRDE vortex shedding anemometer head involved the use of a shedding strut with an equilateral triangular cross section. It was positioned with its apex facing upwind. However, a 'better quality' modulation signal was found to be produced if the strut was rotated such that its base faced upwind. Later, a patent (20) was located that indicated when rectangular struts were used the best vortices were produced if the depth along the flow direction was 2/3 the width perpendicular to it. As a result the strut cross section in the MRDE device was changed to that of an isosceles triangle where the perpendicular height was 2/3 the width of the base. Following an extensive test program this configuration was found to be the one that allowed the widest range of wind speeds to be detected at a given head geometry.

The flow sensor shown in Figure 10.8 represents the design adopted following the above tests.

10.6.2 The design of the vortex detecting electronic circuit

The ultrasonic transducers used in the earlier BA4 air velocity monitor operated at a frequency of 150 kHz. A survey of the market, undertaken at the start of this project revealed that a wider range of cheaper devices was available operating at 40 kHz. As a consequence this type of transducer was adopted for use in the new air flow sensor.

Initially transducers sealed against the ingress of dust were tested. It was found, however, that significant amounts of carrier wave were 'leaking' through the body of the flow sensor resulting in unacceptably high levels of noise on the modulation signal. Not only this, but interference from bench vibrations was also observed during the tests. Consequently, a pair of unsealed transducers was purchased and fitted into the prototype flow sensor. The noise level on the modulation signal showed an immediate reduction and the sensitivity to bench vibrations was also removed. To limit the likelihood of dust becoming a problem, discs of fine (200 mesh) stainless steel gauze were fitted in front of the transducers.

The electronic circuits used in the BA4 air velocity monitor detected the amplitude modulation of the ultrasonic carrier wave caused by the vortices. Development of a similar circuit for use with the MRDE detector head resulted in a version that had too high a current demand (greater than 50 mA) for the battery powered equipment with which it was to be used. However, using an oscilloscope it was observed that the detected ultrasonic signal was not only amplitude modulated but also phase modulated by the vortices. This is as expected. A circuit that detected the frequency of this phase modulation was developed. It was found to be less sensitive to changes in ambient temperature and easier to use than the earlier version. Its current demand was less than 20 mA at a supply voltage in the range 10 to 15V.

A schematic diagram of the MRDE phase modulation detection circuit (MRD 90966) is shown in Figure 10.9. A 40 kHz oscillator was used to drive the ultrasonic transmitter. The detected carrier wave was first converted into a fixed amplitude 40 kHz rectangular wave by the high frequency trigger. The phase of this signal was then compared with that of the transmitted wave and a low frequency ac voltage output (the modulation signal) generated that corresponded to the difference between the two. A trigger

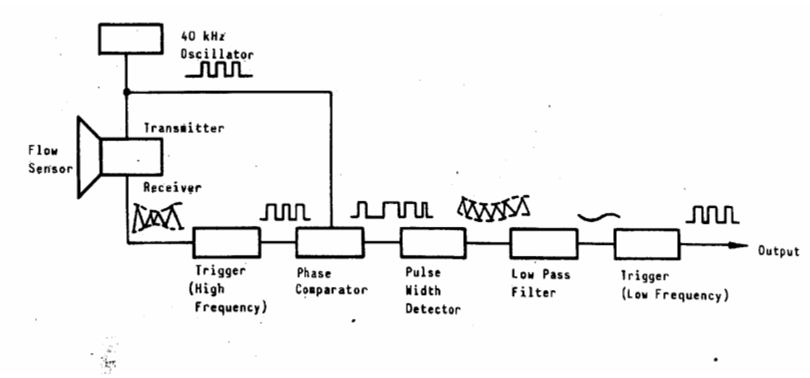


Figure 10.9 The electronic circuit used in the MRDE vortex shedding anemometer detector head (British Coal)

converted this modulation signal into a corresponding rectangular wave with a frequency related to the vortex frequency. The output from the system was typically 500 Hz at a wind speed of 20 m/s.

10.6.3 Tests carried out on the MRDE vortex shedding anemometer detector head

A series of tests intended to investigate the performance of the apparatus under a variety of conditions was conducted on a complete prototype system. This comprised of a flow sensor and phase modulation detection circuit as described above.

It was found that the detector head would operate reliably in wind speeds from approximately 0.22 m/s up to 40 m/s. At the time, no other single vortex shedding anemometer tested had been shown to operate over such a wide range.

In flow rates from 0.3 to 20 m/s, the designed range of operation of the detector head, the maximum deviation of the output frequency from a linear response to a changing wind speed was less than 1% of full span.

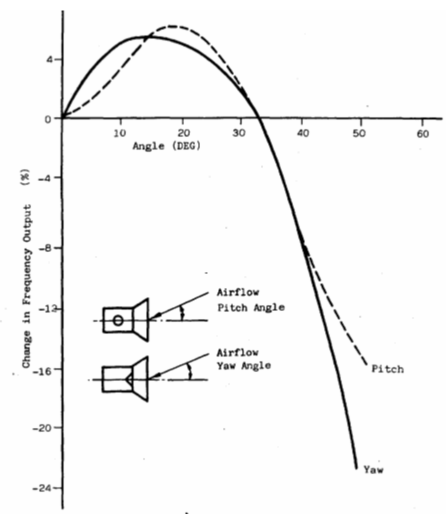


Figure 10.10 The effect of pitch an yaw angle on the output from the MRDE anemometer detector head (British Coal)

No tests were conducted into the effects of changing the temperature and pressure of the air flow past the detector head, due to lack of suitable apparatus at MRDE Calculations indicate, however, that changes likely to occur in a coal mine would not affect the performance of the apparatus. Experiments conducted in still air at temperatures from 0 to 40^{o}C showed no variation in the level of noise on the modulation signal.

The variation of output frequency with pitch and yaw angle is shown in Figure 10.10. The results show a steadily rising error with angle, reaching a maximum of 6% between 10 and 20^{o}. Further increase in the pitch/yaw reduced the positive error and introduced a negative one instead. It is interesting to compare this diagram with that shown in Figure 8.11 for rotating vane anemometers. Bearing in mind the scale of the two ordinates are different it will be seen that the graphs are remarkably similar in shape.

The MRDE vortex shedding anemometer detector was designed for application underground in coal mines. Tests were, therefore, conducted to see what effect accumulations of dust would have on the system performance. Initially, a prototype airflow sensor, without the ultrasonic transducers fitted, was installed underground at Daw Mill Colliery. After two months exposure it was examined for accumulations of dust on the various surfaces. Laboratory tests were then conducted using Plasticene to see what maximum build-up of material could occur before the detector head performance was seriously affected. The results showed that layers up to 0.5 mm thick on the mesh screens in front of the transducers and up to 2 mm thick on other surfaces could be tolerated.

In use, regular cleaning of the flow sensor would be advisable to prevent accumulations of dust forming on the upwind side of the strut and in the tapered entry. The ultrasonic transducer faces should be kept vertical, and dirt removed by blowing rather than brushing, to avoid forcing dust through the fine mesh guards.

10.7 The development of the MRDE hand held anemometer

As work on the MRDE vortex shedding anemometer detector head progressed, it became apparent that the final model would be suitable for use in a hand held anemometer system for use in coal mines. The apparatus was to be capable of providing an instantaneous reading of wind speed and also one averaged over any period up to three minutes. This facility would allow the instrument to be used on a zigzag ventilation traverse (see Chapter 2).

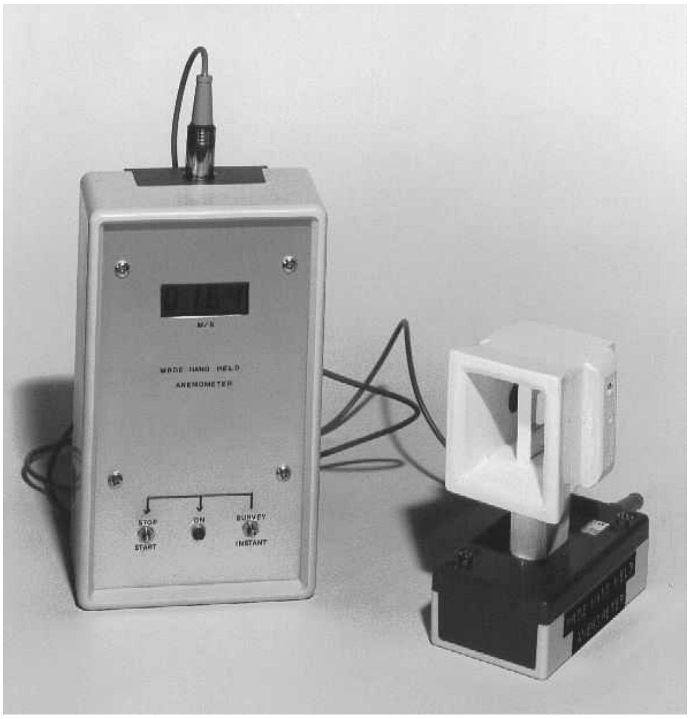


Figure 10.11 The MRDE hand held vortex shedding anemometer
(British Coal)

A complete prototype instrument is shown in Figure 10.11. It consisted of the detector head described above and a control unit. Both were developed by MRDE between 1980 and 1983.

The control unit housed a signal processing circuit, shown in schematic form in Figure 10.12. Included in this circuit were: a clock to provide the system timing and control pulses, vortex and time pulse counters, a display counter and a liquid crystal display (LCD) to show the measured wind speed. A rechargeable battery powered the system, allowing about ten hours continuous use.

When the system was switched on, the vortex and time pulse counters were initiated. At the appropriate moment, governed by the LF (low frequency) control sequence, the two gates were opened. Approximately every four seconds, this allowed the time pulse total to be transferred to the inputs of a programmable frequency divider (divide by time pulse count), and the vortex pulse total to the inputs of a ‘down counter’. The output from a high frequency oscillator, used to derive the time pulses, was then simultaneously fed to the ‘clock’ inputs of these two components. Whilst the ‘down counter’ was counting down from the vortex pulse total, the ‘divide by time pulse count’ was enabled, sending a series of pulses to the display counter. The frequency of these pulses was equal to that of the HF (high frequency) clock divided by the total time count. The number received was shown on a four digit LCD. This reading was held until the next ‘down count’ was underway, when the display flashed until the new reading was available. By altering the HF clock frequency, the total number of pulses fed to the display counter could be made to be, for example, 100 at a wind speed of 1.00 m/s and 2000 at 20.00 m/s.

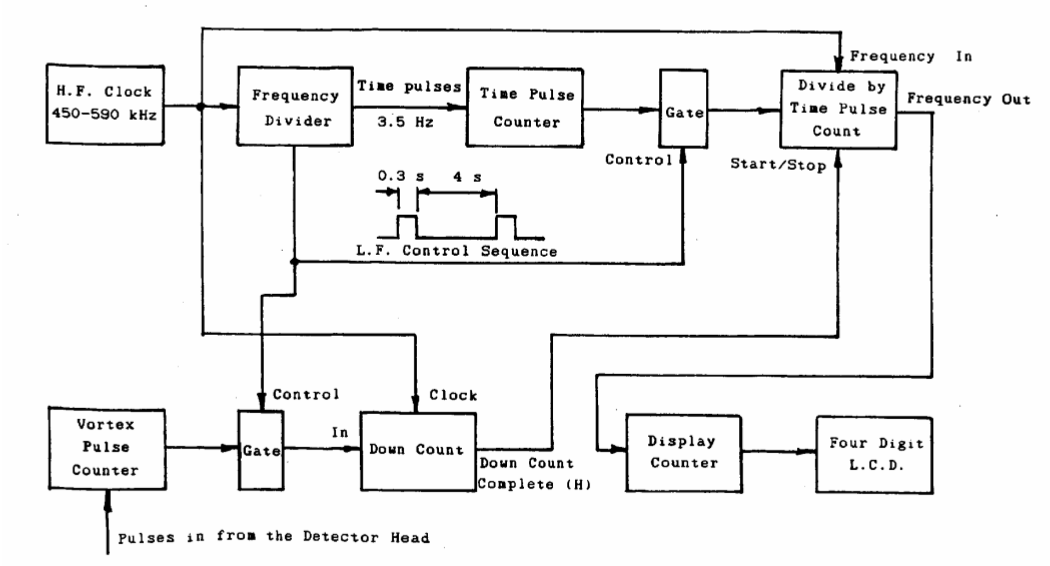


Figure 10.12 A block diagram of the counting circuit in the MRDE hand held anemometer (British Coal)

The MRDE hand held anemometer could be operated in two modes: 'instantaneous' and 'survey'.

In the instantaneous mode, the control pulses reset the vortex and time pulse counters at the end of each count sequence. Thus the reading shown on the meter was that derived from the pulse totals collected over the previous four second period.

In the survey mode, a display of wind speed calculated from the vortex and time pulse total counts collected over any period up to about three minutes could be obtained. When an external switch was moved to 'survey start', both the time and vortex counters were first reset and then initiated. When 'survey stop' was selected, the calculation usually initiated by the LF control sequence started and the average wind speed calculated and displayed. This reading was held until either 'survey start' or 'instantaneous' was selected. During the period of the survey, the LF control sequence continued to provide an indication of the wind speed derived from the total vortex and time pulse counts but without resetting the counters. The maximum survey time depended upon the wind speed; at 20 m/s it was of the order of 3 minutes, rising to about 15 minutes at 4 m/s. These limits were set by the design of the counting circuits. Too long a survey was indicated by an unsteady reading on the display.

The prototype MRDE hand held anemometer was constructed using discrete CMOS digital components. Shortly after its completion a specification covering the further development of the system was issued. Various firms expressed an interest at the time, but it is believed that Trolex Products Limited were the only firm to develop a hand held vortex shedding anemometer. This apparatus was not, however, based on the MRDE design.

10.8 Recent commercially produced vortex shedding anemometers

The MRDE vortex shedding anemometer detector head was originally intended for use in a proposed BA5 air velocity monitoring system. This apparatus was to be similar in its concept to the BA4, but be capable of operating over a wider range of wind speeds. On completion of the work described in Section 10.6, Technitron (UK) Limited and Sieger Limited undertook the commercial development of the system based on the MRDE prototype design.

In 1985, the BA5 air velocity monitor shown in Figure 10.13 received its certificate of intrinsic safety.

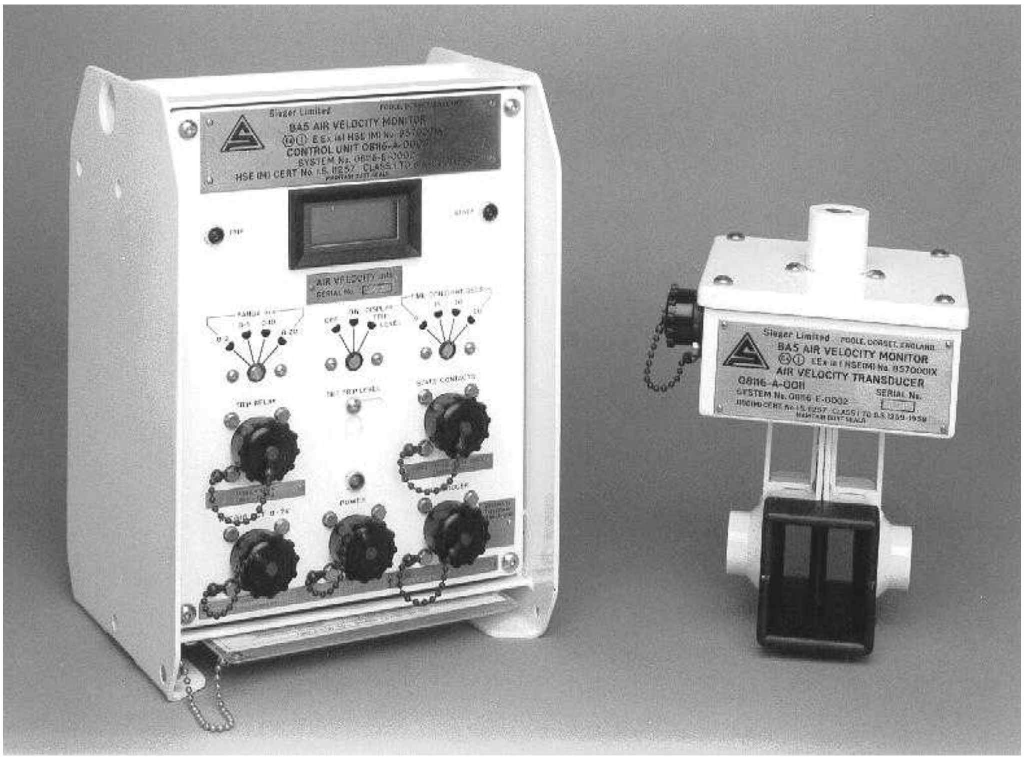


Figure 10.13 The BA5 air velocity monitor (British Coal)

The detector head incorporated many of the features of the original MRDE design, including phase modulation detection and the ‘C’ shaped shield. Whilst maintaining the 2/3 ratio of depth to width, the strut used had a trapezium shaped cross section. This apparently reduced the size of some non-linearities in the system output observed with the prototype design.

The control unit, whose outward appearance was very different from earlier designs of unitised environmental monitors, incorporated a built-in battery power supply and digital LCD display for the wind speed. As with the other instruments, an analogue output in the range 0.4 to 2.0 V was provided, along with standard alarm indications. Four ranges of wind speed corresponded to a full range output from the system. These were: 0 to 2.0 m/s, 0 to 5.0 m/s, 0 to 10.0 m/s and 0 to 20.0 m/s. It is reported (21) that the minimum detectable flow rate is in the region of 0.2 m/s.

Trolex Limited has also produced a series of vortex shedding air flow sensors for use in coal mines. However, they are not based on the MRDE work described above. Designated their TX1320 range, is reported (22) that instruments have been made available to monitor wind speeds up to 40 m/s. In use, an air flow sensor would be connected to a 12 V dc power supply and an analogue monitoring module to display the measured flow. The design of the system would allow one power supply to feed up to four monitors and several monitoring modules to be sited together in one enclosure.

10.9 Use of vortex shedding anemometers in coal mines

The use of vortex shedding flow sensors underground in coal mines has removed some of the problems associated with the use of rotating vanes in damp and dusty conditions. However, in such locations the flow is known to pulse and data is available, for example (23), which leads to the view that this may affect the accuracy of the result provided.

Experiments to investigate the performance of the BA4 in turbulent air flows have been reported by Cohen (24). The results showed that a change in the turbulent intensity (amplitude of the fluctuation divided by the mean flow) from 2 to 12% resulted in a corresponding change in the instrument output of less than 10%. It was remarked that the actual intensities in US mine air flows were believed to be less than 11% and would thus have little effect on the BA4 reading. Measurements made in Britain by Davies and Jones (2) revealed fluctuations in mine air flow as high as 23%. They also commented that they expected this figure to be exceeded in working districts. The practical implications that the presence of such flow pulsations are likely to have on the use of vortex shedding anemometers in British coal mines have yet to be investigated.

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Chapter 11 Pressure difference anemometers

The pressure acting at any point in the bulk of a stationary fluid, the static pressure, is the same in all directions. In a moving fluid the total pressure along the direction of the flow is found to be larger than the static pressure acting perpendicular to it. The difference between these two, called the velocity pressure, has been shown to be proportional to the square of the fluid speed.

A number of anemometers have been designed using these principles. This chapter describes their historical development, making particular reference to those used in coal mines. Pressure difference flow sensors for mounting in the ducts of auxiliary ventilation systems will be discussed in Chapter 13.

11.1 The development of pressure difference anemometers

What was probably the first pressure tube anemometer is reported (1) to have been described some time before 1721 by Pierre Daniel Huet, Bishop of Avranches in Normandy, France. The apparatus consisted of a vertical, open ended, 'U' tube containing mercury. One arm had its end bent through ninety degrees, allowing the opening to be pointed at the wind. The difference in the heights of the mercury columns in the two vertical tubes was proportional to the pressure exerted by the moving fluid, and consequently the square of the flow rate.

Stephen Hales, an English parson who had a particular interest in the ventilation of ships and buildings, described a similar device in 1743. This apparatus was filled with water, making it more sensitive to low flows (1).

On the 12 November 1732, Henri de Pitot, the Superintendent of the Canal du Midi in Languedoc, France, described equipment he had used to measure the flow speed of rivers. The apparatus consisted of two vertical open ended tubes mounted parallel to one another on a wooden frame. The bottom end of one was bent through ninety degrees, whilst the other was cut square to its axis. When the lower end of the apparatus was immersed in the river with the bent tube facing the flow, river water rose up the tubes to a height that was dependant upon the pressures at the openings. The difference in the lengths of the two columns of water was proportional to the velocity pressure (2)(3).

Even at the time Pitot designed his apparatus, it was accepted that the velocity pressure was proportional to the square of the flow speed. The size of the constant in the equation was, however, open to argument. Unfortunately Pitot chose the wrong value and the speeds he calculated were incorrect (2)(3).

In 1775, James Lind described (4) a pressure tube anemometer that was, according to (1), the first practical instrument of its kind. The apparatus, shown in Figure 11.1, consisted of a glass 'U' tube half filled with water. The vertical limbs were about 10 mm in diameter and 150 mm long. At the point where they joined it was reduced to 2.5 mm. A brass elbow was fitted over one tube end and a perforated cap over the other. A scale was provided to allow the difference in the height of the liquid columns to be determined.

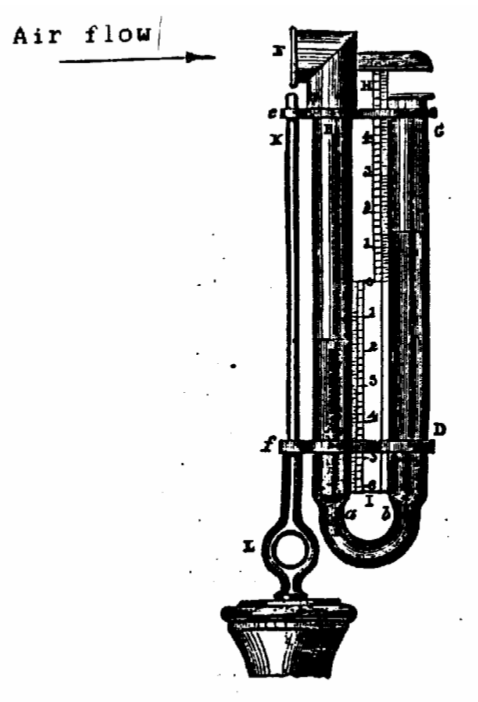

Figure 11.1 Lind's anemometer (Reproduced by kind permission of the Colliery Guardian)

To measure wind speed, the apparatus was positioned with opening of the brass elbow facing the flow. This allowed the total pressure to be registered. The square cut tube was intended to measure the static pressure, with the difference in heights of the two liquid columns being proportional to the velocity pressure. Any oscillation of the indication caused by the pulsation of the wind was partially eliminated by the damping introduced by the reduction in tube diameter at the joint of the vertical limbs.

A James Ferguson is reported (4) to have tested Lind's anemometer on a whirling arm (see Chapter 14) and found that the indication was proportional to the square of the input wind speed. However, a consequential insensitivity to low flows tended to restrict its use in coal mines. Some one hundred and twenty five years after its invention Stokes reported (5) that Lind's anemometer could be used in those well ventilated mines where the wind speed was greater than 1260 ft/min (6.4 m/s).

In addition to its low sensitivity there was another problem associated with Lind's anemometer. This occurred as a result of the use of a large diameter tube to measure static pressure. In practice, eddies would have been created in its mouth, leading to a constant of proportionality between the fluid column height and flow that was a function of flow. Theoretically, this meant that the calibration of the instrument could not be derived from first principles and chart had to be provided for each instrument. However, from Ferguson's results the effects of not doing this were seemingly not significant.

The first steps towards the modern Pitot static tube, whose performance could be accurately predicted from theory, were taken by the French engineer Henri Philibert Gaspard Darcy. Sometime between 1856 and 1858 he developed a pressure difference flow meter (for use in the measurement of water speed) where the total and static pressure sensing tubes were combined in a single head and not separate like Lind's. The total pressure was detected through a small hole in the end of a tapered tube whilst the static was detected using a pipe with its end cut parallel to the flow (6). A 'U' tube manometer was probably connected to the apparatus via rubber hoses to measure the velocity pressure (total minus static).

During the first decade of this century, a rising interest in aeronautics caused the British National Physical Laboratory (NPL) to conduct an examination of a range of anemometers that had potential application in this work. Most required some form of calibration before they could be used and were thus considered unsatisfactory. One exception was the pressure tube anemometer. Consequently, subsequent years saw the evolution of the NPL Pitot static tube and a number of investigations into its characteristics. References to such occur from about 1909 onwards (7).

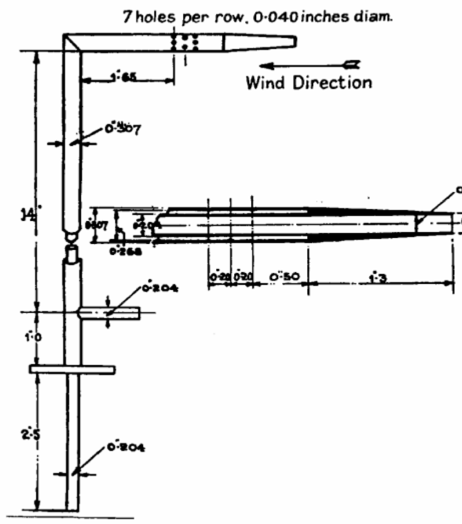

Figure 11.2 The NPL tapered Pitot static tube (Reproduced by kind permission of Chapman and Hall

An NPL combined Pitot (total) and static pressure flow sensor dating from about 1912 is shown in Figure 11.2. It consisted of a total head tube surrounded by, but sealed from, a coaxial static tube. A series of small holes in the latter allowed the pressure to be sensed. In use the apparatus was aligned with the flow and the pressure sensing tubes connected to a sensitive differential pressure indicator to give the velocity pressure (8).

From Bernoulli's theorem it can be shown that the velocity pressure (p) associated with moving air at subsonic speeds is related to its speed (v) via:

$$p = \frac{1}{2} r v^2 \qquad 11.1$$

where ρ is the air density. In practice the design of pressure tube flow sensors sometimes means that the true velocity pressure is not obtained and an equation of the form:

$$p = \frac{1}{2} k r v^2 \qquad 11.2$$

must be used, where k is an experimentally determined constant. Ideally this should be as close to unity as possible and independent of flow rate.

For the NPL Pitot static tube shown in Figure 11.2 it has been found (8) that from about 6 to 15 m/s the assumption of unity ‘k’ only resulted in errors in the velocity indications provided of about 0.1%. Subsequent experience showed, however, that these could be considerably larger if the instrument was not aligned with the flow. Further, the tapered nose of the apparatus was susceptible to mechanical damage. Again this could give rise to large reading errors (9).

In 1925, Ower and Johansen (10) reported the results to a detailed investigation into how the design of Pitot static tubes influenced the measurement of static pressure. It was found that if the sensing holes were less than five tube diameters from the instrument’s upwind end the detected pressure varied with position. The presence of the stem tended to increase the indicated static pressure on its upwind side. At fifteen tube diameters this increase was found to be less than 0.5% of the velocity pressure. This study was not extended to cover the measurement of the total pressure because there was considered to be adequate evidence to show that the shape of the forward facing tube did not affect the detected value.

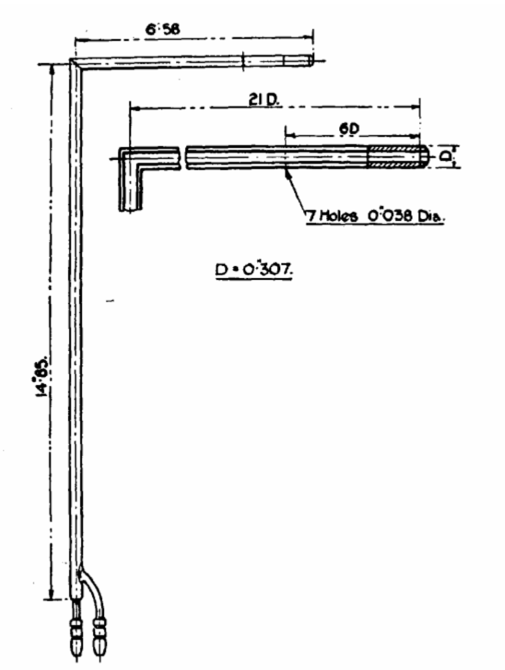

Figure 11.3 Ower and Johansen’s hemispherical Pitot static tube (Reproduced by kind permission of Chapman and Hall Limited)

As a result of their investigation Ower and Johansen were able to design a new Pitot static tube. Shown in Figure 11.3, this instrument incorporated a hemispherical head to reduce the potential significance of any mechanical damage that may occur. Tests showed that at angles greater than about 15^o the effect of yaw on the new instrument was considerably less than with the older device (10).

At about the same time as the hemispherical Pitot static tube was being developed in this country, in Germany Ludwig Prandtl was working on his own pressure tube flow sensor. Outwardly similar to the former, it included annular slots to sense the static pressure. Prandtl tubes have been preferred for use in dusty atmospheres where small static holes are liable to become blocked.

With the NPL hemispherical Pitot static tubes it has been found that as the input flow speed falls, ‘k’ in 11.2 deviates from unity, resulting in measurement errors of about 6% in the region of 0.6 m/s (11). In an attempt to improve this aspect of the instrument’s performance, without at the same time introducing significant alterations into its

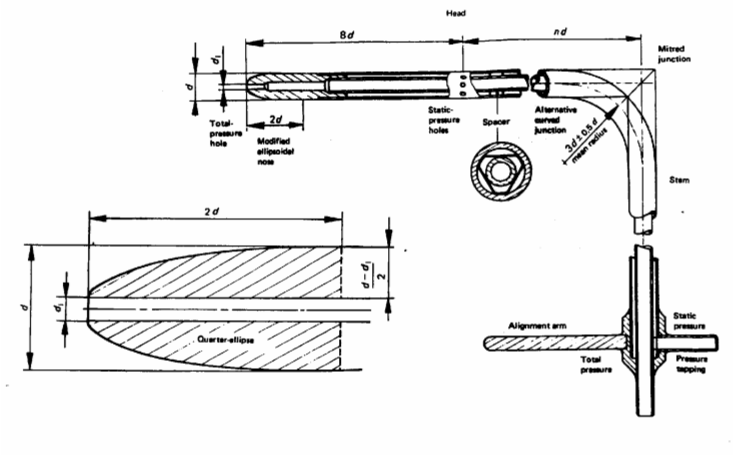

Figure 11.4 The ellipsoidal Pitot static tube from B.S. 1042:1983 (14) (Reproduced by kind permission of the British Standards Institution)

other characteristics, Kettle (12) produced a Pitot static tube with an elliptical shaped nose. Later, a slightly modified device was described by Salter, Warsap and Goodman (13). This has subsequently been adopted for use in tests specified by the British Standards Institution (14). A drawing of the standard Pitot static tube is given as Figure 11.4. It has been shown that this apparatus is insensitive to small changes in its dimensions, such as occur during the manufacture of large numbers. The value of ‘k’ has been found to be unity over a wind speed range from 13 to 60 m/s. Further, it is believed that if this assumed value is applied at speeds from 1 to 60 m/s the resulting errors will be less than 0.5 % (11).

The insensitivity of Pitot static tubes to low flow rates and the attendant need to measure very small differential pressures accurately have tended to limit their use in coal mines. The most common areas of application are in the measurement of air flow in the ducts of auxiliary ventilation systems and fan drifts. Further consideration of the former application is provided in Chapter 13.

Over the years attempts have been made to produce pressure tube anemometers that generate higher differential outputs than the Pitot static tube in the same flow (k greater than unity). This would increase the versatility of such devices by removing the associated need to use very sensitive pressure measurement instrumentation. This is typically fragile and difficult to use in location such as those found underground in coal mines.

One such ‘amplifying anemometer’ is that shown in Figure 11.5. It was developed by in France by Bourdon during the latter half of the nineteenth century (15). This apparatus is of interest because, although it was never apparently used in this country, it was developed for coal mine use and thus represents an early illustration of how the needs of the coal mining industry led to new forms of pressure tube anemometer. Its design was based on that of the Venturi tube, a type of flow meter usually associated with measurements in closed conduits. Briefly, this consists of two truncated cones joined together at their apexes such that they produce a short section of pipe with a reduced cross sectional area. As the fluid passes into this throat it is accelerated. It can be shown that the consequential reduction in the static pressure below that of the free stream is proportional to the square of the flow rate. Bourdon placed a multiplicity of Venturi tubes inside one another and mounted them in a mine roadway. One pressure tapping to the measuring manometer was positioned in the throat if the innermost tube whilst the other sensed the atmospheric pressure in the roadway.

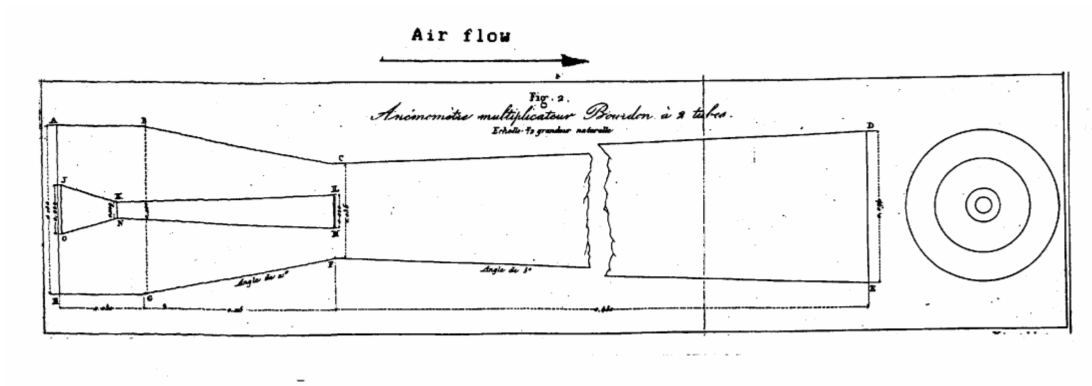

Figure 11.5 Bourdon’s anemometer

Early tests were carried out on a two tube Bourdon anemometer in the mines of Bessages, in the South of France (15). The results showed an increase in output pressure over that of a Pitot static tube (magnification factor) of 7.9 at 2.3 m/s, rising to 14.0 at 6.8 m/s, the upper limit of the experiments. Later trials on a three tube device returned magnification factors of 48 at 1.1 m/s and 80 at 12.7 m/s (5). However, when the apparatus was tested at two different sites the magnification factors showed a 7% difference.

Despite this apparent variation of performance with location, and other factors, Bourdon’s anemometer did find used in British coal mines. In these instances, an output pressure pipe was connected to remote indicating devices invented by Mr Hall, HM Inspector of mines, in 1891. This could be placed in the manager’s office (24).

Hall’s indicator was made by John Woods, a clock and instrument maker of Rainhill, Lancashire, and is shown in Figure 11.6. It included a circular chart over which a pen moved. This was raised and lowered by changes in the pressure across a manometer, one limb of which was connected to Bourdon’s anemometer. The chart was rotated by a clockwork mechanism (24).

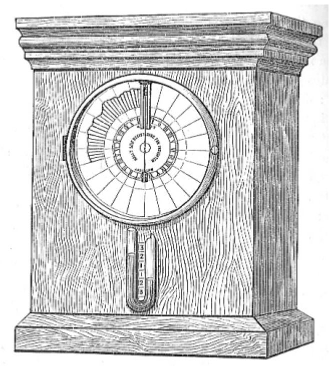

Figure 11.6 Hall’s indicator (24)

In the early 1920’s, J. L. Hodgson, of George Kent Limited also developed a pressure tube anemometer that generated a higher output than a Pitot static tube in the same wind speed (16). This apparatus used the fact that the pressure on the down stream face of a cylinder in a fluid flow is below the static pressure. Shown in Figure 11.7, it consisted of a cylinder with two pressure tapings, one on the upstream face and the other on the downstream. It was claimed that the differential pressure generated was proportional to the square of the wind speed down to below 0.1 m/s. Hodgson’s pressure tube anemometer was used in British coal mines up to the middle 1930’s.

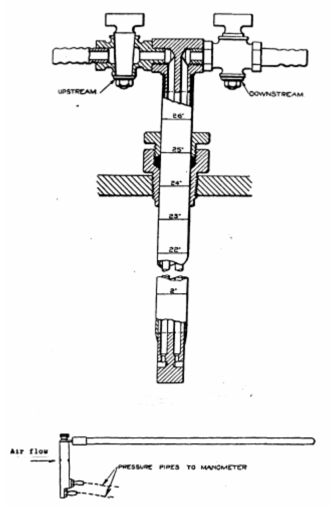

Figure 11.7 Hodgson’s Pitot tip (Reproduced by kind permission of the South Wales Institute of Engineers)

11.2 The measurement of differential pressure

One of the commonest methods of measuring the differential pressure generated by a pressure tube anemometer is to connect the two output pipes (total and static) to the opposite ends of a vertically mounted ‘U’ tube part filled with liquid. Such apparatus is called a manometer. Using this approach, the required pressure reading ‘P’ is given by:

$$P = hrg \qquad 11.3$$

where ‘h’ is the difference in the heights of the liquid in the two limbs, þ’ the liquid density, and ‘g’ the acceleration due to gravity.

One of the problems associated with the use of pressure tube anemometers has been the accurate measurement of the very small differences in vertical liquid column height produced by the lower speed flows. To some extent, his has been overcome by producing ‘inclined tube’ manometers. With such apparatus one or both of the ‘U’ tube limbs are inclined to the vertical. If ‘α’ is the angle of inclination and ‘L’ the length of the liquid column supported, then the applied pressure ‘P’ is given by:

$$P = Lrg\sin(a) \qquad 11.4$$

From this it will be seen that for angles other than 90^o for a given pressure P, L will always be greater than h in 11.3.

An early reference to an inclined tube manometer is due to Dickinson (17). In an attempt to develop a sensitive pressure tube anemometer based on that of Lind, he had constructed an instrument in which one limb was a bulb and the other inclined such that it rose about 3 inches (76 mm) in 3 foot (914 mm). The apparatus is said to have been made in 1853 by Mr Casartelli, an instrument maker of Manchester. It did not, however, ever come into common use. Later, in a report of the nineteenth century Prussian Firedamp Commission (18), it was stated that inclined tube manometers had been used in conjunction with Pitot tubes to measure air flow in the drifts of mine ventilating fans.

Currently, companies such as Airflow Developments Limited manufacture inclined tube manometers that are seemingly similar lines to that described by Dickinson. They use a large diameter reservoir connected to a smaller diameter inclined tube. This arrangement allows the input differential pressure to be determined directly from measurements of the length of the fluid column in the tube.

The velocity pressure, and hence length of manometer fluid column, associated with a moving fluid is proportional to the square of the wind speed. To provide a manometer where the length of the fluid column varies linearly with velocity it is necessary to make sin(α) in 11.4 a function of L. It results in a curved tube device.

A ‘curved tube’ manometer was described by the British meteorologist William Henry Dines in 1893 (19). Later, in the 1920’s and as a result of experiences gained using pressure tube anemometers to measure mine air flows, one was also developed by Hodgson. Containing light oil as a working fluid to avoid the need for its continual replacement due to evaporation, it is shown in Figure 11.8. The system was subsequently produced commercially by George Kent Limited (20).

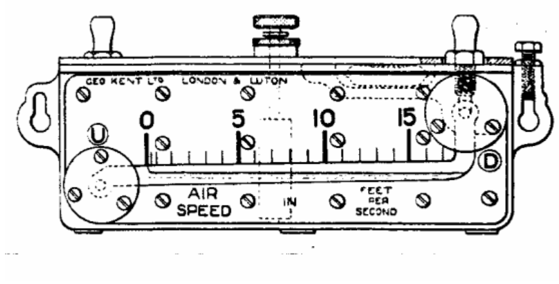

Figure 11.8 The George Kent curved tube manometer (Reproduced by kind permission of the South Wales Institute of Engineers)

Liquid filled manometers are not very convenient to use underground in coal mines. As an alternative, ‘Magnahelic’ gauges manufactured by Dwyer Instruments in the USA are available. With these, the input differential pressure is applied to the opposite sides of a diaphragm. Connected to this, via a magnetic linkage, is a pointer that is caused to move over a scale calibrated in the appropriate units. Devices are available covering a range of input differential pressures. They are relatively robust and very easy to use. One drawback is that, being un-powered, they have no means by which the results can be electrically recorded or transmitted to a remote location.

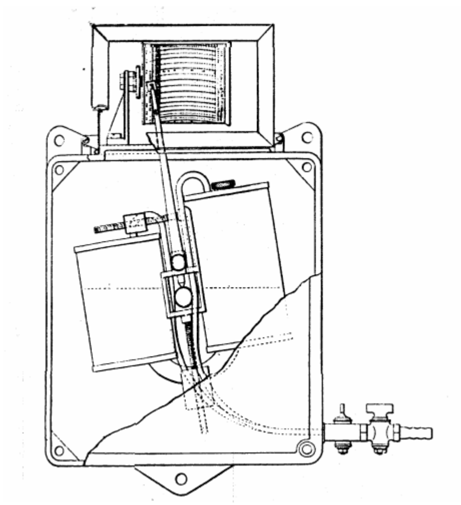

Figure 11.9 Hodgson’s pressure recorder (Reproduced by kind permission of the South Wales Institute of Engineers)

11.3 Pressure recorders

Chapter 3 has already described how recording manometers were used from the early 1880’s to monitor the pressure generated by mine ventilators. A later paper on the subject by Stokes (5) lists in excess of a dozen different devices of this kind.

In 1898-9 Murgue mentioned (21) how a recording manometer was connected to a Pitot tube and used in French coal mines.

An early example of a British recording pressure tube anemometer is due to Lander in 1905-6 (22). He used pressure to expand and contract a bellows mounted beneath the pen of a recorder. As the pressure increased, the bellows got larger and lifted the pen up, drawing a line on the chart. A dash-pot was provided to damp out any oscillations due to fluctuating flow. Although described as being an anemometer, the apparatus had only one pressure tapping. It could, therefore, not be used to measure the differential pressure from a source such as a Pitot static tube where the static pressure at the sensing point was substantially different from that at the recorder.

Later, in 1925-6, Hodgson described (16) a sensitive pressure recorder for use with his pressure tube anemometer described in Section 11.1. The apparatus, shown in Figure 11.9, consisted of two connected reservoirs that were partly filled with oil. They were balanced on a knife edge. The two pressure tappings on the flow sensor were joined one to each drum. Any pressure differences forced oil from one reservoir to the other. This upset the balance of the system and moved the pen over the chart. The literature does not make it clear how many of these manometers were actually used in coal mines.

A paper (23) published in 1935-6 contains a discussion of the possibility of using an inverted bell type pressure recorder in a coal mine anemometer system. This type of instrument was similar to a meteorological anemograph developed by Dines (1). A schematic diagram of the proposed apparatus is shown in Figure 11.10. It consisted of an inverted cup floating in a sealed tank containing water. The two pressure tappings of the Pitot tube were connected to the apparatus as shown. Any excess of pressure inside the cup caused it to rise, moving the pen across the chart. It can be shown that vertical movement of the pen is greater than the equivalent changes in water column height by an amount determined by the geometry of the system. No evidence appears to exist as regards the application of this, or similar, apparatus underground.

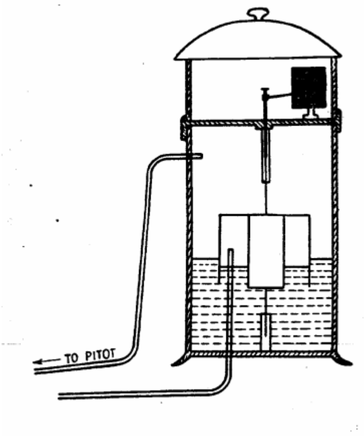

Figure 11.10 The inverted bell pressure recorder (Reproduced by kind permission of the Institution of Mining Engineers)

11.4 The use of pressure tube anemometers in pulsing flows

When a pressure tube anemometer is used to measure turbulent flows, such as those found in coal mines, it is observed that the height of the liquid column in the manometer oscillates. This makes it very difficult to obtain a reading of velocity pressure. One way of reducing these oscillations is to include some form of viscous damping in the pipes joining the pressure tube to the manometer. This can be done by inserting capillary tubes, or porous cotton wool plugs, in the lines (11).

It should be noted that the use of the mean velocity pressure in equation 11.2 will not give the mean velocity, but the root mean square (rms) value. For an oscillatory function the rms value is greater than the mean.

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Chapter 12 Hot body anemometers

Anyone who has had reason to use expressions such as ‘cooling breeze’, or ‘biting wind’, will be able to testify to the cooling power of moving air. The sensations that prompt these comments show that if an object is hotter than its surroundings then it will lose heat at a rate dependent upon, amongst other things, the wind speed past it and the air temperature.

This chapter describes the development of anemometers for use in coal mines in which wind speed is deduced from observations of the rate of cooling of a hot body situated in the flow. Two forms of anemometer will be discussed, those that use heated thermometers, and those that incorporate electrically heated wires and thermistors.

12.1 Hot thermometers

The cooling sensation felt by a human in an air flow was probably one of the first uses of ‘hot body’ anemometry in coal mines. Although no quantitative measurements were obtained in this way, writing in 1858 Smyth (1) says that an experienced miner was able to tell whether the air current was sufficient or not by this method.

The fact that wind speed could be determined from a measurement of the rate of cooling of a hot thermometer was probably first proposed in 1804 by Sir John Leslie, the Scots mathematician and physicist (2). During an investigation into the propagation of heat he had found that a hot body cooled faster in moving air than it did if the air was still. By whirling a tin globe filled with hot water around on the end of a string he was subsequently able to produce an empirical formula relating its rate of cooling to the relative air speed. Having done this, Leslie then proposed that it be used in the construction of an anemometer. This was to incorporate an alcohol filled thermometer that was initially heated and then allowed to cool in the air current being assessed. Its bulb was to be at least 1.5 inches (38 mm) in diameter, or somewhat larger than a conventional instrument. Later reference to the work (3) indicates that Leslie never put his ideas into practice or make his hot thermometer anemometer.

Professor J. Phillips FRS, of King College London, was possibly the first person to make use of a hot thermometer anemometer underground in a coal mine. In 1849 he was asked by the Government to conduct an inquiry into the state of the ventilation in British mines. Having found that the currents were too sluggish to be registered by candles, gunpowder smoke and mechanical anemometers, he decided to make practical use of Leslie’s ideas on anemometry. The apparatus used consisted of a standard alcohol filled thermometer. This was first heated up and then exposed to the air current. The time taken for the temperature to fall from 10 to 5^{o}F above ambient was measured. An empirically derived formula was then used to calculate the corresponding wind speed. This showed that the flow rate was inversely proportional to the square of the measured cooling time (3).

When Phillips presented his report to the Government in 1850 (4), no mention is made of the hot thermometer anemometer. Assistance in the search for an explanation for this omission is provided by the transactions of the British Association for the Advancement of Science for 1849 (3). This states that very large variations had been found in coal face air flow across the country. Phillips did not want to mention it because it may have led to: ‘erroneous conclusions regarding the relative safety and good management of mines, and prejudice inquiries now on foot’. Is this a suggestion that he felt obliged, or was requested, to keep quiet about the poor conditions he had found?

Prior to carrying out his mining investigations, Phillips had been considering the possibility of measuring wind speed from observations of the rate of evaporation of a liquid under the action of an air current. The method and apparatus used were similar to that described above, with the exception that the bulb of the thermometer was covered with a cloth sleeve soaked with the liquid. The rate of evaporation was determined from the speed with which the indicated temperature fell. This was shown to be related to wind speed (5). Phillips did not, apparently, use this apparatus in a coal mine.

The work of Phillips and Leslie was either forgotten, or possibly ignored, by later workers.

In 1916, Hill et al (6) published a description of an instrument called the ‘kata thermometer’. This had been designed for investigations into the ability of humans to keep cool in the thermal environment. It consisted of an alcohol filled thermometer, the glass bulb of which was 4 cm long and 2 cm in diameter.

The stem was graduated in 0.2° intervals from 90 to 110°F (32.2 to 43.3°C). By observing the time taken for the temperature to fall by a known amount, usually 5°, the 'cooling power' of the environment could be determined. To investigate the effects of surface moisture on the rate of cooling, the kata thermometer could be fitted with a wet muslin sleeve.

Experiments carried out using the kata thermometer indicated, as shown earlier by Phillips using similar apparatus, that wind speed could be measured using both the wet and dry instruments. It was found that for the dry thermometer, the rate of heat loss (H) was related to the wind speed (v) via:

$$H = \left(a + b\sqrt{v}\right)q \qquad 12.1$$

where 'a' and 'b' were numerical constants. 'θ' was the difference, in degrees Centigrade, between ambient temperature and 36.5°C (97.7°F), the mean temperature of the range of cooling. For the wet kata, the rate of cooling (H^I) was given by:

$$H^I = \left(a + b\sqrt[3]{v}\right)q^I \qquad 12.2$$

In this expression 'v' is again the wind speed and 'a' and 'b' numerical constants. 'θ^I' is the difference between 36.5°C and the ambient wet bulb temperature.

The performance of the kata thermometer as an anemometer was investigated at wind speeds from 0.05 to 17 m/s. For both devices, it was found that one set of constants had to be used in 12.1 and 12.2 below 1 m/s and another above this (7).

Rees reports (8) that from about 1920 onwards the kata thermometer was used underground to measure wind speeds on the coal face. It was also used to investigate the problems associated with working in hot and humid conditions.

One of the advantages of the hot thermometer anemometer was that it could be used to sense wind speeds of less than about 1 m/s. These were below the operational range of the mechanical instruments then available for use in coal mines. They did, however, have their disadvantages, including a complexity of use. Also, extra difficulties began to occur in some of the deepest mines where the temperature of the air approached that of the heated thermometer (9). Further, the evaluation formula could not be easily solved underground, but had to be done on the surface (10).

12.2 Electrically heated wires and thermistors

In view of the difficulties associated with the use of the kata thermometer as an anemometer and the insensitivity of other forms, during the 1920's it was felt that there was a need within the coal mining industry for a direct reading anemometer that would accurately respond to low wind speeds. Hot wire anemometers were developed in an attempt to fulfil this requirement.

An electrically heated wire suspended in an air stream will loose heat at a rate that is dependant upon the flow rate. If the power supplied to the system is kept constant, the temperature, and hence resistance, of the wire will also be related to the flow rate.

It is not clear why people started investigating the effects of moving air on heated wires, but according to King (11) the problem was receiving considerable attention from both theoretical and experimental physicists from about 1820 onwards. In 1910, a Dr Kennelly in the USA is reported to have suggested that the rate of cooling of a hot wire could be used as the basis of an automatic recording anemometer. From the results to a series of experiments, he was able to show that the rate of heat loss from a thin heated copper wire was proportional to its temperature above ambient and to the square root of the wind speed past it (12).

The first person to report the construction and application of a hot wire anemometer in this country was Professor J. T. Morris, or MacGregor-Morris as he is later referred to, in 1912 (12). Initially he made use of system operating at constant temperature. With this type of apparatus, the flow sensing wire is maintained at a constant temperature, as indicated by its resistance, by adjusting the applied current and voltage. The product of supply voltage and current were found to be proportional to the square root of the wind speed.

During his early studies, Morris discovered that the calibration of his constant temperature instrument changed with amb ient conditions. To overcome this problem he began using a constant voltage anemometer. This instrument was first described in 1920 (13) and is reported to have been designed for coal mine use. With such devices the power dissipated by a wire exposed to an air current, and hence the current drawn from the supply, can be related to wind speed. Alternatively, the current through the wire can be kept constant and the voltage used as a measure of the power input and flow rate.

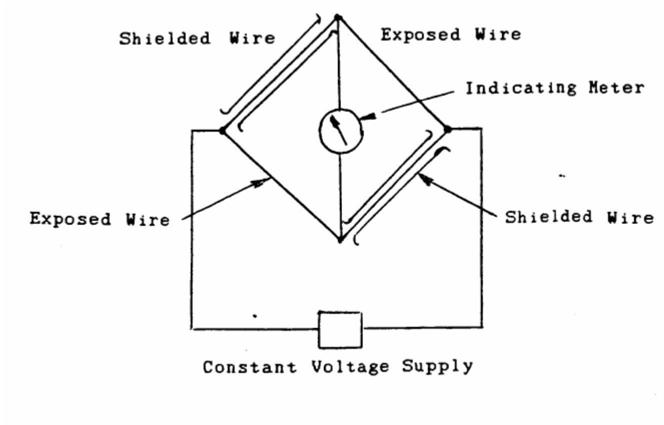

Figure 12.1 A schematic diagram of the 1920 Morris hot wire anemometer

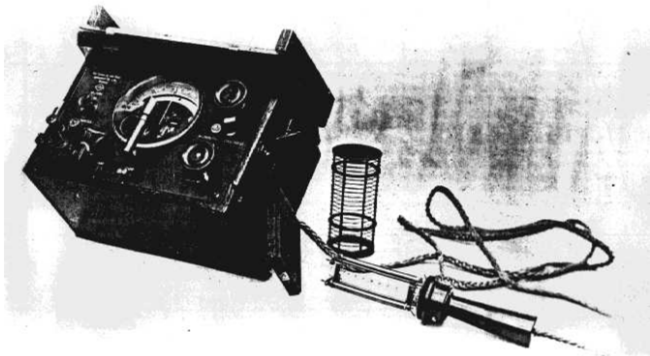

Figure 12.2 The 1920 Morris hot wire anemometer
(Negative Number 2492 reproduced from the archives of the Cambridge Instrument Co Ltd by kind permission of Cambridge University Library)

The 1920 Morris hot wire anemometer is shown in Figures 12.1 and 12.2. The system consisted of four heated nickel wires formed into a Wheatstone bridge. Two of the elements in the circuit were shielded from the air current, whilst the others were exposed to it. Any changes in the air temperature affected all four hot wires equally, maintaining the same relative values of resistance in both arms of the bridge. If the air flow rate changed, then only the resistance of the two exposed elements were altered, unbalancing the bridge. This out of balance signal was displayed on a meter. The hot wires were mounted together on a detector head that was connected to an indicator unit containing a meter and a battery power supply.

To use the apparatus, it was first necessary to set the wire temperatures to the correct value above ambient in still air. Once this had been done, the flow sensor could then be exposed to the air current and the reading on the meter noted. A calibration chart was used to convert this into an indication of wind speed. The instrument is reported to have responded to flow rates from 0.5 to 5 mph (0.22 to 2.2 m/s).

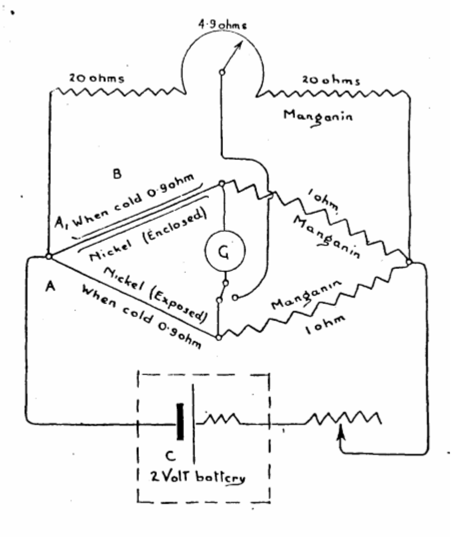

Figure 12.3 The circuit diagram of the 1926 MacGregor-Morris hot wire anemometer
(Reproduced by kind permission of the Colliery Guardian)

Sometime between 1920 and 1926, following comments made by the Institution of Mining Engineers, the Morris hot wire anemometer underwent further development (10), becoming the MacGregor-Morris anemometer. This later instrument is shown in Figures 12.3 and 12.4. A Wheatstone bridge circuit was used to monitor the relative resistances of a hot wire shielded from the flow and one that was exposed to it. The out of balance signal, from which the wind speed was derived, was shown on a meter (9). Unlike the earlier anemometer this version was operated from a constant current source. Components were included that allowed finer control of the wire temperature than was previously possible. The actual set temperature above ambient varied from instrument to instrument, but was generally in the region of 20^{o}C (14).

The photograph given as Figure 12.4 shows the mechanical arrangement of the MacGregor-Morris anemometer. For coal mine use the cable linking the detector head to the indicator unit was 9 ft (2.7 m) long. The fine flow sensing wires were protected by a mesh screen and non-spilling batteries were used (9).

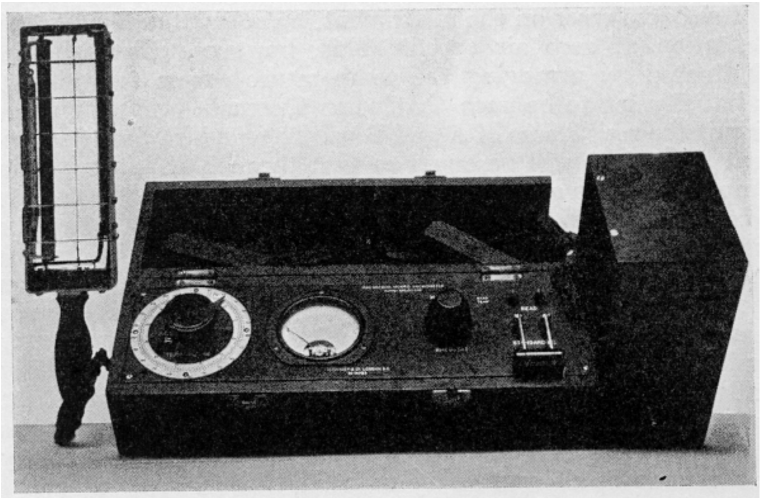

Figure 12.4 The 1926 MacGregor-Morris hot wire anemometer
(Reproduced by kind permission of Chapman and Hall Limited)

Early versions of the Morris hot wire anemometer were developed in conjunction with the Cambridge and Paul Instrument Company Limited. However, H. Tinsley and Company Limited were selling the instrument by 1932 (14).

Hot wire anemometers of the MacGregor-Morris type were used by Rees (10) and Hancock (9) to measure coal face air flows. Rees conducted a survey of forty six working places, and found that at 80% of them the wind speed was less than 0.5 m/s. Hancock took his measurements on an afternoon shift when the ventilating fan had been switched off. He recorded wind speeds as low as 0.01 m/s. Both authors reported that the air flow pulsed.

In his discussion of the use of the hot wire anemometer, Rees noted that the flow sensing wires were extremely delicate, and had to be kept clear of dust to avoid changes in instrument calibration. To try and overcome these particular problems, the National Physical Laboratory (NPL) devised the shielded hot wire anemometer. In this, the sensor was formed from a twin bore silica tube. This is shown in schematic form in Figure 12.5. It was heated by passing an electric current through the 'hot wire', whilst the thermocouple, whose hot junction was in the other bore of the silica tube and cold junction in the 'cold' air stream, was used to monitor the temperature of the assembly above ambient. When placed in an air stream, the flow past the silica tube cooled it. This in turn led to a reduction in the thermocouple output voltage from which the wind speed could be determined. The shielded hot wire anemometer was first described in 1947 (15).

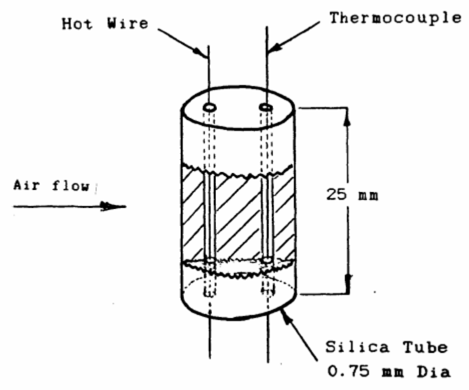

Figure 12.5 A schematic diagram of the flow sensor used in the shielded hot wire anemometer

Also in 1947, it was reported (16) that the Safety in Mines Research Board had developed a recording anemometer incorporating the NPL shielded sensor. The system was intended for use in a study of the safety problems associated with air flows of less than 0.1 m/s underground in coal mines. It is stated that the shielded hot wire anemometer was chosen because it had a high sensitivity, was comparatively robust and, with a heater temperature of 120^{o}C, would not ignite firedamp. Tests showed that the expected changes in environmental variables such as temperature, pressure and relative humidity would not appreciably alter the instrument calibration. It was also found that, under normal operating conditions, dust did not collect on the silica tube. Even when material was artificially applied, the calibration of the instrument remained unaffected.

In 1949 the invention of the shielded hot wire anemometer was attributed to Simmons (17).

MRE carried out tests on a heated resistance anemometer in 1965. It is not known precisely what form this instrument took, but it seems to have had a single scale indicating up to 25 m/s. When tested in damp and dusty conditions similar to those found in coal mines it was found that the instrument performance was seriously affected. Another problem noted during the investigation was that the zero setting required frequent re-adjustment. It was concluded that this particular hot wire anemometer was not suitable for use underground in coal mines (18).

From the late 1960’s onwards the NCB became increasingly interested in the development of continuously operating anemometers. Both the Central Engineering Establishment and Mining Research and Development Establishment carried out investigations into the use of hot wire anemometers in this application.

In 1968 Hilyer (19) reported the development by CEE and English Electric Company Limited of a continuously operating hot wire air flow switch for use in auxiliary ventilation systems. This apparatus is discussed in Chapter 13.

As part of its program to develop a fixed anemometer, in about 1975 MRDE tested the Maihak Ventor. This instrument was first described in Germany in about 1965. It consisted primarily of a Prandtl tube (see Chapter 11) with the total and static pressure tappings linked intemally. The differential pressure generated by an impacting wind generated an internal flow. This was detected using a hot wire flow sensor. Not being certified for use in British coal mines, the Ventor was only tested in the laboratory. Attempts to trace reports of this work have failed, but Browning (20) states that the instrument was rejected for use within the NCB because of dust contamination problems and cost.

Thermistors are small semiconductor devices with a large temperature coefficient of resistance. These have also been used in hot body anemometers operating on the same general principles as their hot wire counterparts. One of the earliest descriptions of a thermistor anemometer is due to Suzuki (21) in 1959. This was apparently designed for coal mine use.

In 1969, Froger (22) reported that the Centre d'Etudes et Recherches des Charbonnages de France (CERCHAR) had developed a thermistor anemometer for permanent installation in a coal mine. This instrument, called the ATM-689 and manufactured by Societe d’Etudes pour l’Electronique et les Mecanismes Automatiques (SEPEMA), was evaluated by MRDE to assess its potential suitability for use in British coal mines. A discussion of the results to laboratory tests reveals (23) that its performance was considered ‘reasonable’ down to a wind speed of 0.3 m/s. However, it was noted that the power consumption was high and that an integral dust filter had to be changed regularly. Underground trials were carried out at Daw Mill Colliery where an un-powered instrument was suspended in a roadway. Periodically, the apparatus was removed and its calibration checked in the laboratory. Over a five week period it was found that the accumulations of dust did not affect the calibration of the instrument. In the end, no further action was taken as regards the use of the ATM-689 in British coal mines. It is speculated (20) that this may have been due to the effects of dust and moisture on the instrument’s output in still air. However, at this time MRDE were investigating the possible use of vortex shedding anemometers. These were considered to be potentially more suitable for coal mines.

As far as it has been possible to ascertain, it is believed that there are no intrinsically safe hot body anemometers in general use in British coal mines.

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Chapter 13 The development of flow sensors for auxiliary ventilation systems

In his report on the accident at Tower Colliery in 1962 (see Chapter 4), Leigh (1) recommended that all power to a heading be switched off in the event of a failure in the air supply. This comment was seemingly instrumental in the subsequent development of sensors to monitor the flow of air in the ducts of auxiliary ventilation systems. Initially simple mechanical flow switches were used. This chapter describes how problems with this type of device led to the introduction of air velocity transducers that generated a differential pressure output that was related to flow rate.

13.1 The use of flow sensors in auxiliary ventilation systems

Loss of ventilation at the face of a heading can, for example, be due to a fault at the fan or a break in the ducting part way along its length. To ensure that problems such as these are detected quickly it is necessary to fit a flow monitor inside the duct as close to its delivery end as possible. The apparatus must be robust enough to withstand shocks, such as those due to the firing of explosives in close proximity and from rough handling. It must also be convenient to use, otherwise it will not be moved forward as the heading advances. Should the air supply fail, the power to the heading must be switched off. The alarm must also be raised, both on site underground and on the surface. Modern flow sensors are also required to provide an analogue indication of the air quantity flowing in the duct.

13.2 Mechanical and electrical flow switches

One of the earliest forms of flow sensor permanently installed in the ducts of auxiliary ventilation systems were similar in their concept to the freely suspended plate anemometers described in Chapter 7. Briefly, they typically consisted of a plate suspended from a spindle. This part of the assembly would be mounted in the duct. Joined to one end of the suspension arm would be a tilt switch. Mounted in a box outside the duct, it served to activate any alarms connected in circuit. When the conditions were considered acceptable, the plate deflection was arranged such that the tilt switch was in the 'on guard' state. However, in the event of the flow falling, the plate would fall, allowing the switch to operate, raising the alarm as it did so. With some systems the trigger point could be altered by fitting different sized plates.

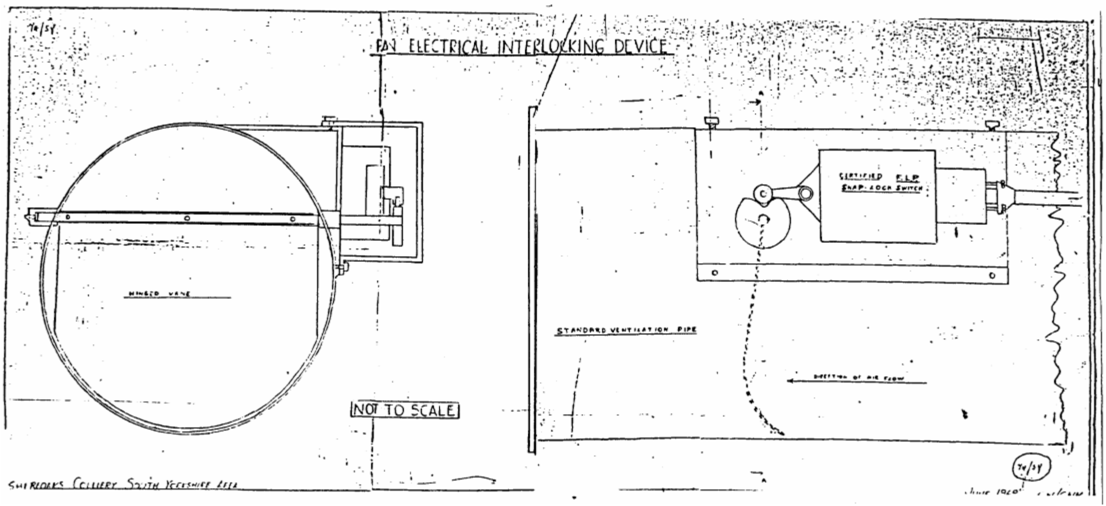

Figure 13.1 Wilde's flow switch for use in the ducts of auxiliary ventilation systems (British Coal)

A mechanical duct flow switch was designed by a Mr Wilde at Shireoaks Colliery in Yorkshire. It is shown in Figure 13.1. The apparatus was made in the form of a short length of standard steel ducting for ease of installation underground. It has not been possible to ascertain how widespread the use of this system was.

An investigation into the use of mechanical flow switches was carried out by MRDE in about 1970. It was concluded (2) that they had an unstable response and that this made them difficult to use. Further, it was considered (3) that they tended to be too fragile for mine use and that their reliance on moving parts could lead to reliability problems in dusty environments. By 1971 the use of such apparatus is reported (4) to have ceased.

As an alternative to mechanical flow switches, CEE and English Electric Company Limited developed a flow switch using the principles of the hot wire anemometer. The detector head of the system is shown in Figure 13.2. Two heated elements were formed into a Wheatstone bridge circuit. One of these was exposed to the moving air, whilst the other was shielded. When the flow rate was at the desired level the bridge was balanced. If the wind speed past the exposed wire changed the balance of the system was upset. When an electronic circuit sensed that the degree of unbalance, and hence change in flow rate, had exceeded a pre-set level the alarm was raised. It is reported (3) that the hot wire flow switch was satisfactorily tested in the laboratory and underground. Unfortunately no information has come to light concerning the subsequent fate of this device.

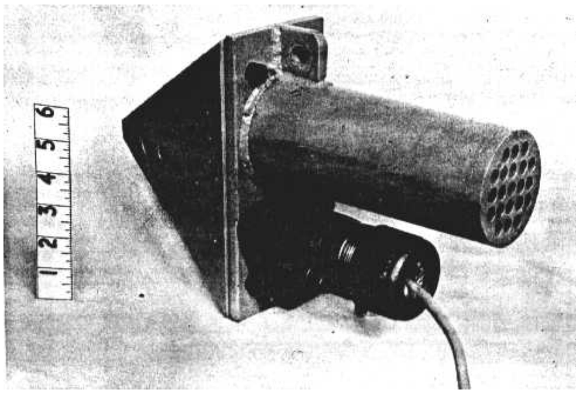

Figure 13.2 The CEE hot wire flow switch (British Coal)

13.3 Differential pressure flow monitors

As a result of the problems associated with the use of flap type flow switches, MRDE started work on instruments that could sense the velocity pressure of the moving air in a ventilation duct (5).

One early system, developed in 1971/2, consisted of a short length of ducting containing an un-streamlined axial boss. This contained a static pressure sensor and had three total pressure sensors arranged about it over the duct cross section. However, when the apparatus was tested it was found that the pressure output was unstable, making calibration of the apparatus difficult (6).

To overcome these problems a new device called the Duct Velocity Alarm (DVA) was designed (6). One example produced from about 1977 onwards is shown in Figure 13.3. It was formed as a short section of duct that contained the flow transducer and also acted as a support for the signal processing and display components. These were contained in the externally mounted enclosure shown. This whole arrangement made for a compact and convenient to use system that could easily be moved forward as the auxiliary ventilation system advanced into a heading.

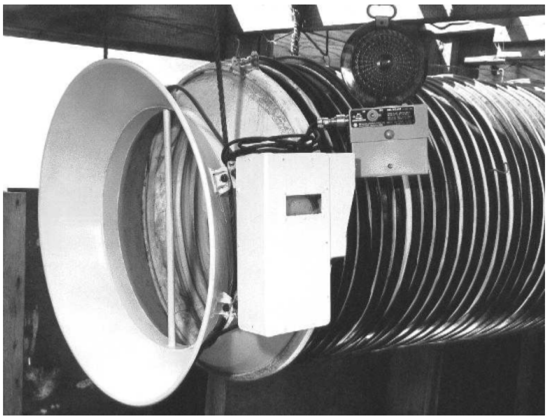

Figure 13.3 The Duct Velocity Alarm (British Coal)

Early versions of the DVA used a forward facing total pressure sensor mounted on the central axis of the duct. The static pressure was measured at the wall. In practice, however, the system was found to be inadequately sensitive to low flows. To increase differential pressure generated by a given air quantity a new transducer was constructed. This was formed from a tube mounted across the diameter of the DVA. The total pressure tapping was on the upwind face and a negative pressure tapping on the downwind. Both were positioned on the duct axis. With the pressure on the rear face of the diametric pipe being less than the static pressure of the fluid, the result was a larger output than a conventional Pitot static tube at all flow rates. To further enhance the sensitivity of the DVA, the ‘double conical’ form shown in the photograph was adopted.

The pressure output from the DVA was typically within the range from 8 to 500 Pa. This was fed to a Magnahelic pressure gauge (see Chapter 11), pre-calibrated in quantity units, for local display of the flow. It was also fed to a diaphragm switch. Both were housed in a steel box fixed to the outside of the apparatus. Externally accessible sockets allowed alarm indicators, such as the Plessey Multi-flash just seen at the extreme right of Figure 13.3, to be connected to the contacts of the diaphragm switch. These were activated if the flow fell below a pre-set level.

Suitable for inclusion in both forcing and exhausting ventilation systems, the DVA would be mounted on the end of a duct, or possibly a short distance back to avoid damage from shot firing. It has subsequently been widely used underground in British coal mines.

In the late 1970's a duct mounted differential pressure type flow sensor called the 'Duct Flow Grid' was seen in use in the North Derbyshire Area of the NCB. It was manufactured by Airflow Developments Limited. The apparatus consisted of a short length of steel ducting containing a grid of small diameter pipes, formed in a plane perpendicular to the air flow. Four of these pipes had a multiplicity of slots cut in their upwind faces. These were linked together and connected to the 'total' pressure tapping of an inclined manometer situated outside of the duct. The other four pipes had slots cut in their downwind faces and were joined to the 'static' pressure side of the manometer. The air flow quantity would have been determined from the indicated differential pressure, possibly using a calibration chart.

Over the years detailed descriptions of the apparatus seen in the North Derbyshire Area have been lost, along with information concerning any tests that may have been carried out on it. It is not known how many Duct Flow Grids were used in coal mines.

On some exhaust auxiliary ventilation systems, in-line filters have been used to reduce the levels of dust discharged into the main mine air current. If these become blocked the supply of fresh air to the heading will fall. To provide warning of such a condition, duct mounted air flow monitors are required to be positioned upwind of the filters. Tests using the DVA and also Pitot static tubes showed that in such an application the pressure sensing holes rapidly became blocked, rendering them useless (7).

In 1983, Graumann and Gastberg in Germany published a paper (8) describing a new type of pressure type air flow sensor. With this, a single up-wind facing total pressure tapping was shielded behind a hemispherical baffle. The static pressure was measured on the down wind side of a disc upon which the baffle was mounted. Tests showed that the apparatus was largely unaffected by accumulations of dirt.

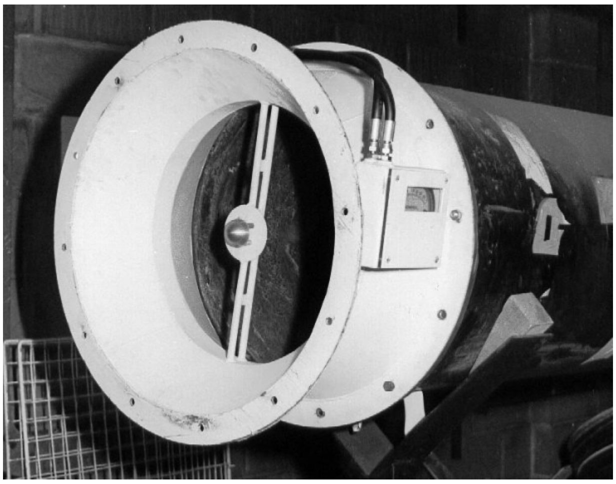

Figure 13.4 The HQTD Air Flow Monitor (British Coal)

To overcome the problems associated with the measurement of air flow near dust filters, British Coal's Headquarters Technical Department (HQTD) developed a duct mounted air flow sensor, designated the 'Air Flow Monitor' (AFM). Based on the apparatus of Graumann and Gastberg, it is shown in Figure 13.4. As with the former, the 'total' pressure sensor was protected by a hemispherical baffle. The 'static' pressure tapping was positioned on the downwind side of its supporting disc. A Magnahelic gauge, mounted in a protective enclosure on the outside of the duct, was used to display the pressure difference generated by the flow. As examples of the performance of the HQTD Air flow Monitor, the minimum flow quantity that could be detected using a 610 mm diameter system was 2 cu m/s whilst for one 760 mm in diameter it was 3.5 cu m/s (9).

One of the limitations of the early versions of the differential pressure type duct flow monitors, such as the DVA, was their inclusion of Magnahelic gauges. This meant that they could only provide a local indication of the flow rate that was not capable of being transmitted using the developing MINOS systems. Consequently, in 1978 MRDE, in association with Sieger Limited, began development work on apparatus that would overcome this shortcoming. The result was the BP2 Pressure Monitoring System. This included a differential pressure transducer that accepted the output from, for example, a DVA, Duct Flow Grid, or AFM flow sensor and converted it into a proportional dc signal in the range 0.4 to 2.0 Volts for transmission to an associated control unit. Here the input voltage was shown on a digital meter calibrated in Pascals. It could also be transmitted on to the surface. Should it fall below a pre-set level a pair of externally accessible relay contacts was caused to pulse at a 1 second rate thus raising the alarm. A range of transducers was available covering input pressures from 0-10 Pa to 0-10 kPa. The whole system was certified as intrinsically safe for use in coal mines (10).

The Duct Velocity Alarm and AFM infer the quantity of air flowing in a duct from a single measurement of wind speed taken on its axis. If the velocity profile were to change, the relationship between the flow sensor output and quantity flow could be expected to change. According to Browning (11), the double cone duct section on these instruments was intended to limit such effects.

Another approach considered by MRDE in an attempt to overcome the potential problems associated with changes in velocity profile affecting duct air flow assessments involved inferring the air quantity from measurements of the static pressure in the plane of the duct end. A similar technique had been used by D'Aubisson (12) as long ago as 1825. More recently, Ower (13) showed that for exhausting systems this pressure was proportional to the mean flow rate. Tests carried out by MRDE confirmed that this was the case. Further, it was about three times greater than the velocity pressure. This would make a flow sensing device based on this approach considerably more sensitive than, for example, a conventional Pitot static tube. As predicted by Ower, close to the end of a forcing system the static pressure was approximately zero. However, it was found that a large diameter orifice plate fitted at the end of the duct could produce a pressure that was proportional to the quantity flow. Results showed that an orifice plate that reduced the discharge area by only 25% generated a static pressure with a magnitude approximately twice that of the velocity pressure. Using these results a prototype static pressure type duct air flow monitor was designed and built in 1984. Tests carried out on the apparatus (14) revealed that the performance was as predicted. Despite this, no further development work was undertaken.

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Chapter 14 The calibration of anemometers

Before an indication of flow rate can be determined from the reading shown by an anemometer the relationship between the two must be obtained. For the Pitot static tube this can be derived theoretically from physical principles. However, for most other anemometers it is necessary to perform a series of experiments to obtain an empirical formula, or table, relating the 'indicated' and 'true' wind speeds.

There are two ways of calibrating an anemometer; one involves moving it at a known speed through still air, and the other requires that air be blown over a stationary instrument. With the former method the true air speed can be calculated by dividing the distance moved by the time taken. As applied within the coal mining industry, the latter technique involves using a standard anemometer to give a reading of wind speed past the un-calibrated instrument.

In addition to a discussion of the more general methodologies of anemometer calibration, this chapter also considers those applied within the British coal mining industry.

14.1 Methods in which the anemometer is moved along a straight line in still air

It is probable that one of the earliest methods used to generate a given wind speed past an anemometer was for the instrument to be held at arms length and carried through still air over a measured distance in a known time. Hooke used this technique in 1683 to demonstrate the effects of blade angle on the speed of rotation of a vane anemometer (1).

More recently, in 1921-2, Cooper (2) conducted a detailed investigation into the use of this method for the calibration of anemometers in wind speeds up to 500 ft/min (2.5 m/s). It was concluded that the results obtained for the instrument correction factors had, '..a degree of precision sufficient for practical purposes'. The author noted, however, that to obtain high speeds it was necessary for the observer to run. This not only jolted the instrument but also produced swirl (component of flow not parallel to the anemometer axis), both of which would have adversely affected the accuracy of the results obtained.

One way of producing 'steady' motion at a high speed was to mount the anemometer on a carriage (3), or in front of a railway engine (4). In the former case it was noted that the method was potentially unsatisfactory because the carriage drew air along with it. This meant that the speed of travel was not the wind speed past the anemometer.

14.2 The whirling arm

An alternative method of calibrating an anemometer by moving it through air at a known speed is to use a 'whirling arm'. This equipment consists of a horizontal beam that is free to rotate about a vertical axis. The anemometer being calibrated is fixed to the arm such that its axis forms a tangent to the circle described by the apparatus. The distance travelled by the anemometer is calculated by multiplying the number of arm revolutions completed by the circumference of the circle swept out. This is then divided by the measurement period to give wind speed. Until the advent of practical wind tunnels, whirling arms were the most widely used method of producing air flows for aerodynamic research. This included the development and calibration of anemometers.

The invention of the whirling arm has been attributed to Benjamin Robins who is reported (5) to have first described his apparatus on the 19th June 1746. At about the same time a Mr Rouse is also believed to have used a similar device (6). Robins's apparatus consisted of a 4 ft (1.22 m) long rod pivoted about one end. A falling weight attached to a string wound around the arm's axle caused it to rotate. The equipment was used to investigate the aerodynamic drag on moving bodies (6).

In 1759 Smeaton used a 5 ft 6 ins (1.68 m) radius whirling arm to investigate the performance of windmills (7). The rotation was produced by an operator pulling on a string wound around the axle of the apparatus. A swinging pendulum was provided to help maintain a constant speed.

Combes (8), in 1838, described the use of a 1 m long whirling arm to determine the calibration coefficients of his rotating vane anemometer described in Chapter 8. The motive power for the apparatus was provided by a clockwork motor. To vary the speed of rotation the angle of two vanes on the motor's fly wheel were changed. This altered the aerodynamic drag on the system and hence the speed of the motor. In use, the anemometer was positioned on the extremity of the arm with its trigger engaged and both indicating wheels set to zero. The whirling arm was then set in motion. After three revolutions, to allow the speed to stabilise, the cord on the anemometer was pulled. This allowed the vanes to rotate. The true wind speed was calculated as described earlier.

Whilst on a visit to Paris in May 1853, Dickinson visited an instrument manufacturer (possibly M. Newman) where he saw Combes's whirling arms being made. On his return to England, he described what he had seen to Casartelli who made an 'improved' version. This device was probably rotated by hand. A falling weight drive mechanism (similar to that used by Robins in 1746) had been added to the apparatus by John Dalglish and Lindsay Wood by the late 1850's (9). This allowed the speed to be varied by altering the size of the weight. Later versions of this whirling arm were made by John Davis and Son, of Derby (10).

In 1861, Atkinson and Dalglish (11) reported the results to an investigation into the performance of rotating vane anemometers. Initially a hand rotated whirling arm was used. However, it was found that a constant speed could not be maintained and so a weight driven system was used instead. This is shown in Figure 14.1. Tests were conducted using two different sized arms, one describing a 10 ft (3 m) circumference circle, and the other 25 ft (7.6 m). With the smaller of these, the anemometer vanes did not appear to rotate at a uniform rate. At first this was attributed to unsteadiness in the arm's motion, but later experiments showed that it was more likely to have been due to turbulence created by the system as it moved. Also, it was found that the anemometer calibration curves obtained using the two sized arms were different. Consequently, the anemometers under test were re-calibrated by walking them in a straight line in still air. This gave in yet another set of results. Atkinson and Dalglish did not know which were correct and were thus forced to conclude that further work was required to investigate the calibration of anemometers.

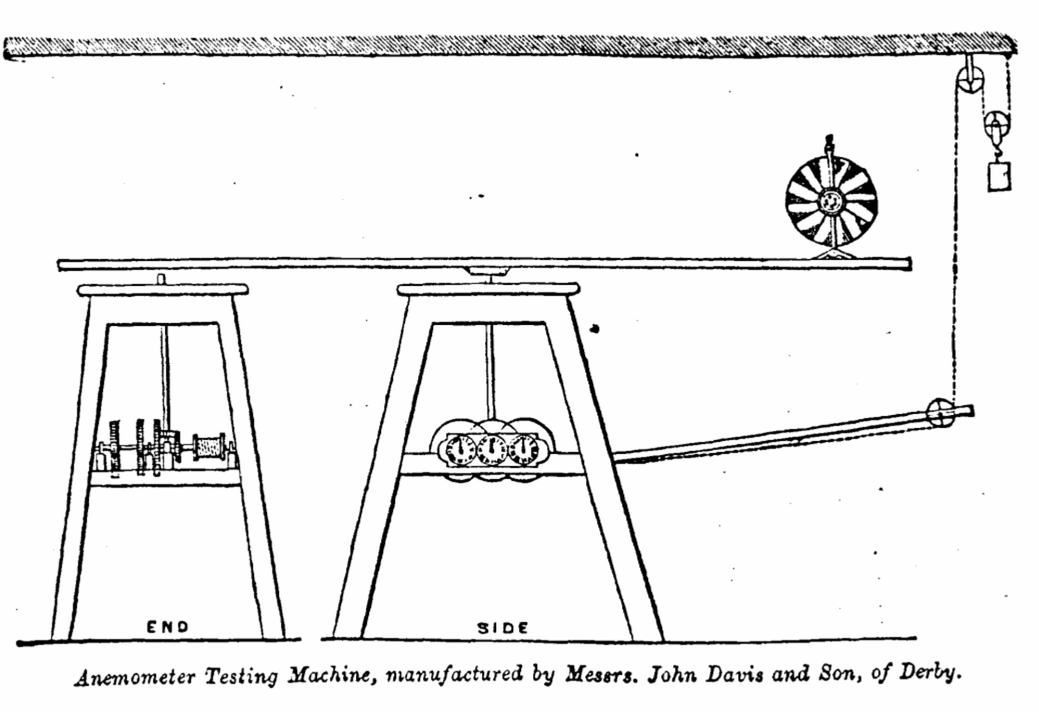

Figure 14.1 A whirling arm manufactured by Davis and Sons of Derby (Reproduced by kind permission of the Colliery Guardian)

In 1898, Rateau (12) conducted experiments into the effect of whirling arm radius on anemometer calibration factors. He found that it affected both coefficients 'a' and 'b' in Equations 8.1 and 8.2. Quantitative data from Cooper shows (2) that at a wind speed of about 1 m/s anemometer correction factors necessary to give the true value from the indicated varied from 0% of instrument reading at an arm radius of 0.3 m up to about 30% at 2 m. This variation in factor fell with rising wind speed. It was concluded that anemometers were unreliable in low air velocities. However, in reality it was probably the calibration that was unreliable.

The report of a similar study carried out by the Safety in Mines Research Board in 1936 (13) included a note to the effect that 'swirl' produced by the whirling arm apparatus as it rotated had a serious effect on the anemometer calibration. This 'swirl' is air that is dragged around with the instrument under test and means that its speed relative to the ground is not the same as that of the air current past it. Measurements of swirl velocity have been made by Bramwell et al (14) in 1912. They used sensitive rotating vane anemometers positioned just outside the circumference of the arm. Similar measurements have been made by King (15) using hot wire anemometers.

Despite the problems associated with the use of whirling arms, they were widely used for the calibration of anemometers well into this century. For example, apparatus of this type was set up at Heriot-Watt College, Edinburgh in 1920 for the testing of colliery instruments. This apparatus was similar in its operating principles to those described above, with the exception that the motive power was provided by an electric motor. Facilities were provided to allow the anemometer trigger mechanism to be operated whilst the arm was in motion.

Uncertainties in the results obtained from the calibration of rotating vane anemometers on the whirling arm eventually led to their replacement by wind tunnels. Nowadays such apparatus is typically used for specialised research and the fundamental calibration of anemometers, such as hot wire instruments. These are used as transfer standards for the subsequent calibration of wind tunnels. When used in such a role, experiments are conducted to estimate the effects of swirl on the calibration results obtained.

14.3 Wind tunnels

A wind tunnel is a tube through which air is blown or sucked. Calibration of an anemometer is achieved by comparing its reading with that of a 'standard' instrument in the same flow. This will have been calibrated by a recognised authority, such as the National Maritime Institute, at Teddington, Middlesex.

One of the earliest forms of wind tunnel was developed for laboratory investigations into the performance of high pressure steam jet ventilators for use in coal mines. This apparatus was described to the Select Committee of the House of Lords (16) by Sir Henry Hussey Vivian, a coal owner from Wales, on the 28 June and the 13 July 1849. It consisted of a long, vertical wooden tube, 2 ft (610 mm) square and open at both ends. To its upper end was fixed a 10 ft (3 m) length of 9 inch (229 mm) diameter pipe. This was the blast pipe. Where this joined the wooden tube there was an upward pointing steam jet fed by a Cornish tube boiler with its safety valve set at 50 psi (494 kPa). As steam emerged into the blast pipe, it entrained air causing an air current to flow in the wooden tube. To investigate the ventilating power generated by a range of jet and blast pipe size combinations, a Biram anemometer was placed in the wooden tube. A water filled manometer was used to measure the pressure developed between it interior and atmosphere.

A wind tunnel operating on similar principles to Vivian's apparatus was described by Longridge (17) in 1852. It is shown in schematic form in Figure 14.2.

In 1885/6, at about the same time that Engineering described (18) the oft-celebrated wind tunnel of Horatio Phillips, mention was made (19) of a similarly operating steam powered wind

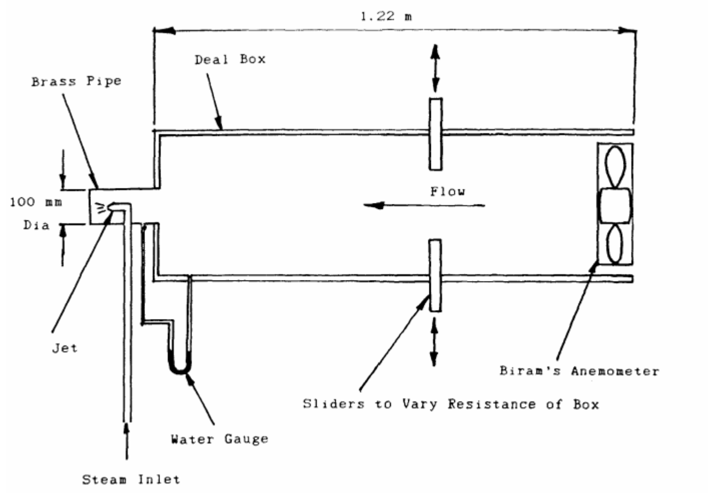

Figure 14.2 A schematic diagram showing the probable layout of Longridge's wind tunnel

tunnel installed at the factory of Messrs. Davis and Son, of Derby. It was 6 ft (1.8 m) long and 15 inch (0.38 m) square. Intended for the calibration of anemometers, the instrument under test was placed in the box upwind of the steam jet and alongside a pre-calibrated 'standard'.

Another early wind tunnel was described in 1867/8 by the North of England Institution of Mining Engineers (20). It was used to investigate the safety of 'flame safety lamps' in flows of flammable gas air mixture. The apparatus, shown in Figure 14.3, consisted of a $11^{1}/_{2}$ inch (290 mm) by $6^{1}/_{2}$ inch (170 mm) by 20 ft (6 m) long tube set up in the return airway of a mine. A pipe led to the mine intake airway allowing the mine ventilating pressure to force the flammable mixture along the tube. A Dickinson plate anemometer was used to monitor flow. Redmayne (21) reported the use of similar apparatus to calibrate anemometers. In this case, the true flow was determined by igniting a small amount of gunpowder at one end and measuring how long it took the smoke to pass along the tube. A sliding regulator enabled the wind speed to be adjusted.

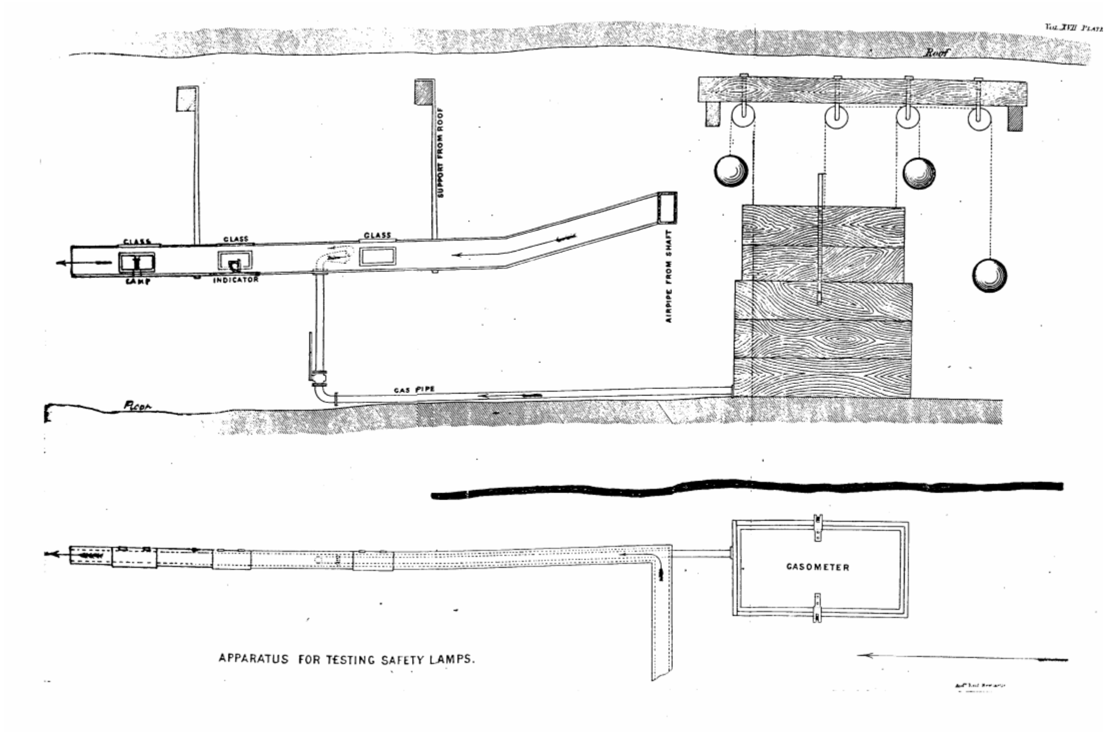

Figure 14.3 A wind tunnel used for testing flame safety lamps in 1867 (Reproduced by kind permission of the North of England Institute of Mining and Mechanical Engineers)

In the early 1870's, the Aeronautical Society of Great Britain asked Francis Herbert Wenham and John Browning to develop a fan powered wind tunnel. Unfortunately the stability of the flow through the resulting apparatus was poor (5) and the aforementioned steam jet wind tunnel of Phillips resulted.

The construction of a fan powered anemometer testing wind tunnel was reported by Simons and Jones (22) in 1927. The apparatus consisted of a 0.3 m square tube joined to a variable speed fan. This sucked air through the system. The anemometer to be calibrated was positioned in a working section upwind of the fan. Precautions taken during the tunnel design ensured that, in operation, the fluctuations in flow rate were less than 2% of the mean value. At wind speeds below about 4.2 m/s the 'true' flow was determined by measuring the pressure drop across perforated plates, or flow grids, inserted in the flow downstream of the instrument under test.

A similar wind tunnel, but with a 0.46 m AF octagonal cross-section, was described by Salter (23). Air was sucked through the apparatus by an axial flow fan driven by a variable speed motor. The maximum speed obtainable was 30 m/s. To allow the flow to be easily set to the desired level three perforated screens, covering wind speed ranges from 0 to 0.6 m/s, 0.6 to 2.0 m/s and 2.0 to 6 m/s, could be inserted to act as baffles. As with the 1927 system, the ‘true’ flow was determined from measurements of the pressure drop across these grids.

A considerable amount of care was taken over the calibration of this later wind tunnel. At high speeds, a Pitot static tube was used, whilst at low floating particles of ‘metafuel’, or a whirling arm calibrated hot wire anemometer were used. Salter reports that provided all the necessary precautions were taken, such as making allowances for the anemometer blockage factor (reduction in tunnel cross sectional area due to the inclusion of the anemometer), then the uncertainty in the tunnel speed was either +/-0.012 m/s, or +/-0.5%, which ever was the largest.

Another form of wind tunnel is the open jet type. One example, manufactured by Airflow Developments Limited, is shown in Figure 14.4. This type differs from those described above in that the anemometer under test is positioned outside the apparatus. To calibrate an instrument against a standard it is necessary to effect a substitution using the turntable arrangement shown. Experience in the use of an open jet wind tunnel has shown that the flow past the anemometer is susceptible to external disturbances, particularly when working at low speeds. Despite this, open jet wind tunnels have been used for many years to investigate the performance of anemometers. For example, Rateau (12) used one in the late nineteenth century to investigate the behaviour of anemometers in pulsing flows.

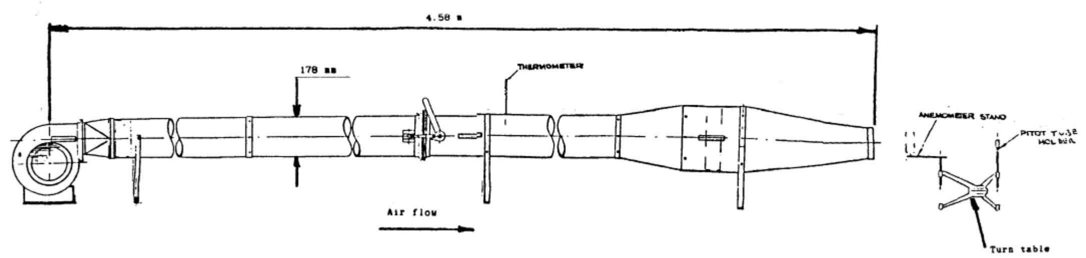

Figure 14.4 The open jet wind tunnel manufactured by Airflow Developments Limited (Reproduced by kind permission of Airflow Developments Limited)

An alternative form of open jet wind tunnel was used by Rees (24) to calibrate his torsion anemometer, described in Chapter 7 in wind speeds below 0.3 m/s. The apparatus consisted of a 18 ft (5.5 m) long, 10 inch (250 mm) diameter steel pipe laid horizontally on the ground. A close fitting piston could be moved from one end to the other by the rotation of a winch handle. In use the anemometer to be calibrated was placed close to one end of the tube. As the handle was turned, the piston moved towards the anemometer, displacing air in the pipe and producing a current of air. A metronome was provided to ensure that the operator rotated the handle at a fixed speed throughout the period of the observation.

14.4 The calibration of anemometers within the British coal mining industry

Before the British coal mining industry was nationalised in 1947, it appears that routine servicing and re-calibration of anemometers used underground was, in some places, virtually unknown. After 1947, and the subsequent collection of the coal mines into a single nationalised organisation, this situation changed, albeit gradually. For example, what was possibly the first NCB anemometer repair and re-calibration department was set up by the North Eastern Division in about 1950. This was equipped with a wind tunnel. Its establishment removed the necessity of having to send instruments through the post to their respective manufacturers for checking. By the early 1960’s the Scottish, North Durham, South Yorkshire, Staffordshire and South Nottinghamshire Areas had followed suit. The Central Engineering Establishment conducted anemometer repairs and re-calibration for a time, but the facility was closed down in January 1968 and the wind tunnel moved to East Wales.

The wind tunnels installed at the NCB anemometer testing stations were, in general, based upon the design described by Salter in N.P.L./Aero/155 (Salter (23) is a revised version of this paper) and shown in

Figure 14.5. The 'true' flow was either obtained using a standard rotating vane anemometer, or the calibrated flow grids described above.

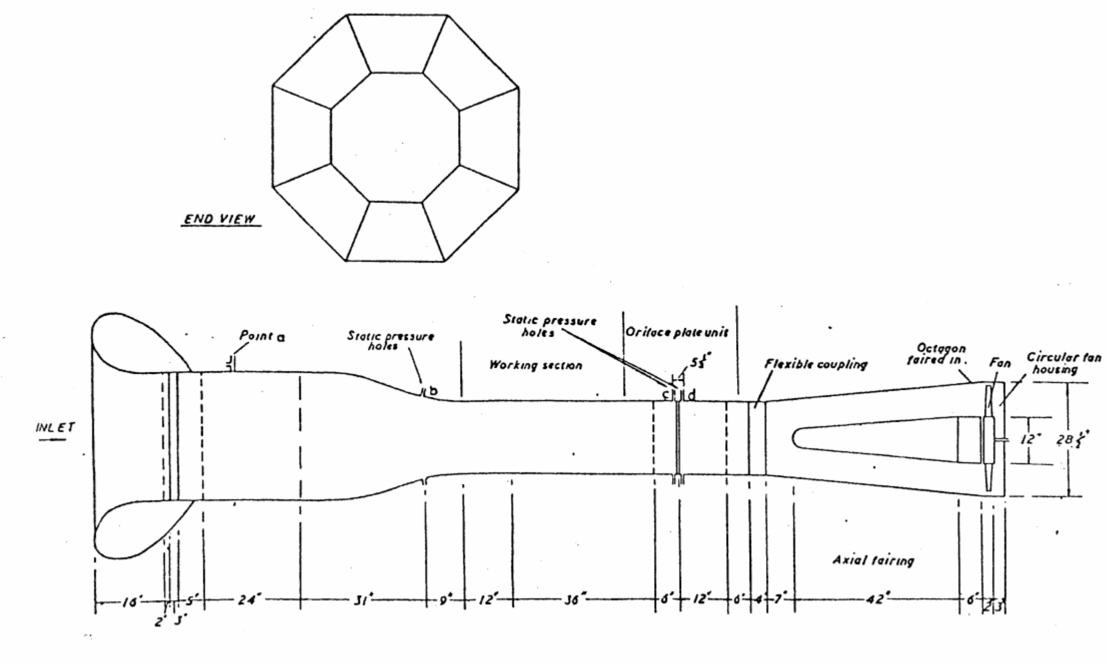

Figure 14.5 The Aero 155, 18 inch, octagonal wind tunnel (British Coal)

Some laboratories attempted to speed up the calibration process by making the standard rotating vane anemometers direct reading. It has already been mentioned in Chapter 9 how Higgins used a capacitive rotation sensor on such apparatus. Bloomfield (25), in the Durham Division of the NCB, sensed the rate of rotation of his standard instrument stroboscopically using what he called a 'strobovisor'.

A draft code of practice for the repair and re-calibration of anemometers within the NCB (26) was issued in 1968. On receipt at a laboratory, each instrument was to be stripped down to its component parts and thoroughly cleaned. It was then checked for damage and reassembled. Each anemometer was calibrated by placing it in a wind tunnel and comparing the indicated wind speed with that calculated from the pressure drop across the flow grid. A table or chart was then produced showing the relationship between the indicated and true wind speeds. This was sent out with the repaired instrument. It was recommended that each anemometer be thus checked twice a year.

The above procedure was still used within British Coal when it was privatised in 1994. However, it is believed that by this time the instrument under test was usually compared with the reading given by a pre-calibrated standard vane anemometer. It is not clear what systems have been adopted for the maintenance of anemometers in the private coal industry.

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Chapter 15 Conclusions

From the evidence presented in this thesis it will be clear that, despite studies being carried out on a wide range of alternatives, rotating vane anemometers have been the type most widely used to determine air flow underground in coal mines. Areas of application include hand held instruments for spot measurements and fixed systems for continuously monitoring the flow at a single site. This longevity of use can be attributed to their relatively wide range of operation, simplicity of use and, in the case of the former, their suitability of use in the zigzag traverse.

Despite their popularity, there is still a considerable degree of uncertainty over the reliability of the results provided by vane anemometers in mine air flows. One particular problem stems from the fact that the speed in underground roadways is known to pulse. Even following studies by MRE and others, there still seems to be an incomplete understanding of the size of these pulsations, the form they take and the effect they are likely to have on the instrument response.

Experimental data suggests that uncertainties from a similar source may exist when the more modern vortex shedding anemometers are used underground. However, no work seems to have been undertaken to investigate this matter.

Since the response of anemometers in underground air flows is uncertain, it is concluded that the results provided are of questionable use in comparing the flows along different roadways in a ventilation network. They may not prove to be accurate enough. To overcome this problem further work needs to be done both to develop an understanding of the flow patterns present and the influence they have in the instrument response.

Provided care is taken over the procedures used, the evidence suggests that the results to air flow measurements at a single site are likely to be repeatable to within a few percent. Consequently a comparison of successive data sets can be used to identify changes in flow that would indicate the presence of a developing fault on the ventilation system.

Problems on a ventilation network can be more readily identified by observing the output from continuously operating anemometer systems. By simultaneously displaying the data from a multiplicity of underground sites at a single point on the surface the colliery management team can see which districts have changing air flows. Further, by comparing the pattern of response of the differing instruments they have the potential for developing an idea as to the likely location of the fault. To fulfil such a role it is concluded that the results merely have to bear a fixed, but not necessarily known, relationship to the actual flow. This means that they are repeatable rather than accurate.

As a consequence of the above, it is concluded that despite the uncertainties in their response underground in coal mines, hand held and fixed anemometer systems play a vital role in the maintenance of safe and healthy conditions in coal mines through their ability to highlight faults on the ventilation network.

APPENDIX I Research organisations within the nationalised British coal industry

In 1947 the British coal industry was nationalised and the National Coal Board (NCB) formed. Contained within the nationalisation act was the requirement that a research and development facility be set up. The result was the Coal Research Establishment (CRE), based at Stoke Orchard near Gloucester.

Initially CRE was involved with both mining research and development and the use of coal. In 1952 the structure and organisation were changed and the Mining Research Establishment (MRE) set up. This organisation took on the responsibility for the mining work. It was located at Isleworth, near London.

Desired improvements in the productivity of the British mining industry required reliable machinery. As a result, and to assist in its development, in 1955 the NCB set up the Central Engineering Establishment (CEE). This was sited at Stanhope-Bretby, near Burton upon Trent.

In addition to the aforementioned ‘central’ research establishments, there was also a number of scientific laboratories distributed within the coal fields. These carried out, for example, the routine servicing of instruments used at the individual mines.

In 1969 MRE and CEE were merged to form the Mining Research and Development Establishment (MRDE) at Stanhope-Bretby. Subsequent contractions in the coal industry resulted in name changes, first to Headquarters Technical Department (HQTD) in 1989 and then Technical Services and Research Executive (TSRE) in about 1990.

The trading name of the National Coal Board was changed to British Coal in 1986. In 1987, the NCB itself was replaced by the British Coal Corporation.

British Coal closed TSRE in April 1994. Further mining research was, however, undertaken under contract by International Mining Consultants Limited. Shortly after, the previously nationalised British coal mines were sold to private operators.

APPENDIX II The use of electrical equipment underground in coal mines

Before being used underground in a coal mine, all electrical equipment must be submitted to a certifying authority for examination. The aim is to ensure that in an atmosphere containing a flammable mixture of methane and air, neither the normal operation of the apparatus, or specified fault conditions, will lead to an ignition of the gas in the general body.

Electrical equipment such as isolating switches, motors and transformers, all operating at high powers, are generally certified as 'Flame-Proof' (FLP). With such apparatus it is accepted that sparks capable of igniting a flammable mixture of methane and air may be produced under normal operating conditions. If an explosion occurs as a result of this sparking, or any other fault condition, then the enclosure containing the equipment is designed to prevent it propagating to the general body. Flame-Proof equipment must not be operated in atmospheres containing more than 1.25% methane in air. The first British Standard covering the design of FLP apparatus was introduced in 1926.

Low powered equipment, such as methanometers, anemometers and communication systems are generally certified as 'Intrinsically Safe' (IS). In the design of such apparatus, safety components are included to ensure that under normal operating conditions, and with a specified number of faults, the power available within the electronic circuit is insufficient to ignite a flammable mixture of methane and air. Provided the appropriate approval has been obtained, some IS systems can be operated in levels of methane in which FLP equipment must be switched off. The first British Standard covering the design of IS apparatus was introduced in 1945. This standard was subsequently revised, and BS 1259:1958 issued. More recently certification to BS 5501 Parts 1 and 7 have also been available. A detailed discussion of the principles of Intrinsic Safety is to be found in Hall (1).

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