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Chapter 6

A CAPACITANCE METER FOR MEASURING TOTAL AIRBORNE COAL DUST CONCENTRATIONS

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ABSTRACT

A dust concentration meter has been developed with Australian coal industry support for the measurement of total airborne dust concentrations capable of causing explosions in underground coal mines. The instrument, The University of Queensland Dust Meter (UQDM), measures the effective dielectric constant of a mixture of coal dust and air that is drawn between the plates of a capacitor, the capacitance of which is measured by a ratio-transformer bridge and synchronous detector system. This technique measures small changes in capacitance to approximately 1 part in 10^6. The unique design of the capacitor sensor permits a precise volume of coal dust and air mixture to be sampled. This arrangement overcomes difficulties inherent in optical dust measurement. The meter is portable, battery powered, incorporates data logging and has intrinsic safety approval.

The operation of the meter is discussed. The system is designed to monitor dust concentrations along a coal mining face and provide concentration profiles leading to the development of suppression strategies. If data from underground tests are available, the meter's potential to contribute to establishing safe working conditions underground will be discussed. Other areas of potential application of the measurement technique are also examined.

INTRODUCTION

Several designs of optical probes for directly monitoring explosible dust concentrations in explosion chambers have been developed by the United States Bureau of Mines (Cashdollar, Liebman and Conti, 1981). However, the measurement principle depends on optical attenuation that relates the number concentration, size, shape and composition of particles that scatter and absorb the light. Practical design constraints also result in instruments with small sampling volumes, creating a measurement bias unless the dust cloud is homogeneously dispersed. Optical surfaces are also easily coated with dust unless special precautions are taken (Liebman, Conti and Cashdollar, 1977).

Slezak and Buckius (1983) developed a β-ray attenuation dust probe for use in a rotating dust flammability tube. β-ray attenuation is well suited to applications involving the monitoring of heavier dust concentrations as the absorption of radiation is directly related to the mass concentration between the source and detector and is largely independent of particle size, shape and chemical composition of the dust. A disadvantage of β-ray attenuation for measuring dust concentrations near the explosible limit, however, is that the air mass of the dust and air mixture contributes to the attenuation and therefore diminishes detector sensitivity to changes in dust concentration. At a dust concentration of 100 g/m^3, the mass of dust is only 8 percent of the total mass of the dust and air mixture. Radiation attenuation is therefore dominated by the air fraction and the sensitivity to small changes in dust concentration is reduced. This dust concentration represents the lower limit of resolution of β-ray measurement methods.

This paper describes the design and operation of the UQDM for monitoring explosible coal dust concentrations in the underground mining environment. An instrument for this application has not been available to the coal mining industry. Nor have conventionally applied dust measurement principles been suitable for developing a dust meter to monitor explosible concentrations. A recent trend in coal mining has been the increasing use of the longwall mining method. The high production rates and confined workings associated with longwalls result in the generation and dispersion of large quantities of fine coal dust. Production rates in the vicinity of 10 000 tonnes per day (tpd) are currently being achieved on Australia's newer longwall faces and 20 000 tpd may regularly be achievable within this decade. In gassy mines, large volumes of methane can be liberated simultaneously. In Central Queensland mines (Australia), seam methane emissions can be high as mining panels move down dip. As there is an increased awareness of the explosion hazard associated with coal dust in the presence of low concentrations of methane, an increased emphasis on the monitoring of both coal dust and methane in the underground mine atmosphere is an important consideration in future strategies designed to reduce the potential for a mine explosion. Thus there is an emerging need for an instrument which can be routinely used for direct monitoring of coal dust in problem areas. The prototype UQDM, which is based on a capacitive micrometry technique, is the first step towards satisfying this need for an industrial instrument.

A rotating explosion chamber developed by Gillies, Robertson and Oldroyd (1990) used a dust concentration probe based on the principle of electrical capacitance (Jensen et al, 1989). The capacitance probe monitors the change in dielectric constant of a coal dust and air mixture between sensing electrodes as the relative composition of the mixture changes. A laboratory dust probe operating on this principle was able to perform satisfactorily in the hostile environment within the explosion chamber. The sampling volume is large in comparison with optical instruments (two orders of magnitude) and the effect of dust settlement on the electrodes was minimized by using a short sampling time. The meter's resolution is approximately 10 g/m^3.

The prototype UQDM design and principle of operation is based on the laboratory instrument. For application to the underground coal mining environment it was designed to be portable and to comply with Australian Standards in relation to intrinsic safety (Standards Association of Australia, 1987, 1989). The probe is temperature and humidity compensated to accommodate underground operating conditions. To automate several measurement modes, the instrument is controlled by a programmable microcontroller with each mode being selected on an alpha-numeric key.

LABORATORY DUST METER

The dust meter probe operates on the principle that the capacitance of two fixed parallel metallic plates (electrodes) depends on the dielectric constant of the insulating material (dielectric) separating them. The value of dielectric constant of air is 1.0006, while values for coal range between 3.5 and 13.0, depending on the carbon content (Groenewege, Schuyer and van Krevelen, 1955; Parkhomenko, 1967). Consequently, as dispersed coal dust displaces air between electrodes the dielectric constant of the mixture increases, as does the probe capacitance. For a simple model of a two-phase mixture where the coal dust and air can be considered as composite layered dielectrics, the capacitance is:

$$C = \frac{\varepsilon_0 A}{d_1/k_1 + d_2/k_2} \qquad (1)$$

where ε_0 is the permittivity of free space, A is the cross-sectional area of each electrode, d_1 and d_2 are the relative thicknesses of the air layer and coal dust and k_1 and k_2 are the dielectric constants of air and coal dust respectively ($\varepsilon = k\varepsilon_0$).

For electrodes of large area and small separation, equation 1 gives a good approximation of the value of the capacitance as the electric field fringe effect at the edges of the capacitor plates is insignificant. Under other conditions, the fringing electric field produces an edge effect which depends on the thicknesses and separation of the electrodes relative to their radii. In order to maintain a representative volume of dust, a practical probe requires an electrode separation of several millimetres but for these separations the edge effect must be minimized. Guard electrodes based on the criteria established by Scott and Curtis (1939) were positioned around the active (measuring) electrodes. Earthed guard electrodes minimize stray field lines and effectively delineate the electric field to the cylindrical volume between active electrodes.

Because variations of the effective dielectric constant of the coal dust and air mixture are small, the measuring system must be capable of precisely measuring small variations in capacitance. Since the capacitance of the probe is also small, a ratio-transformer (RT) bridge system based on the design of Stacey et al (1969) was used. This design has been used for many years by one of the authors (Moore et al, 1988) in geophysics research. Central components of the system are a 5 decade ratio-transformer and a synchronous detector, as shown in Figure 1. A low impedance source (3.0 kHz) drives the RT through an isolation transformer which also supplies the reference signal for the synchronous detector. Provided the active electrodes were not thickly coated with dust, the calibration of the instrument was linear to concentrations of 1400 g/m^3. Accuracy was inversely related to dust concentration, with the maximum measurement error of 10 percent occurring at concentrations of approximately 100 g/m^3.

A standard fixed capacitance C_s and the dust probe capacitance C_p are connected across the ratio-transformer forming a conventional bridge system. At balance:

$$\frac{R}{(1-R)} = \frac{C_p}{C_s} \qquad (2)$$

where R is the transformer reading - a 5 digit number between 0 and 1.

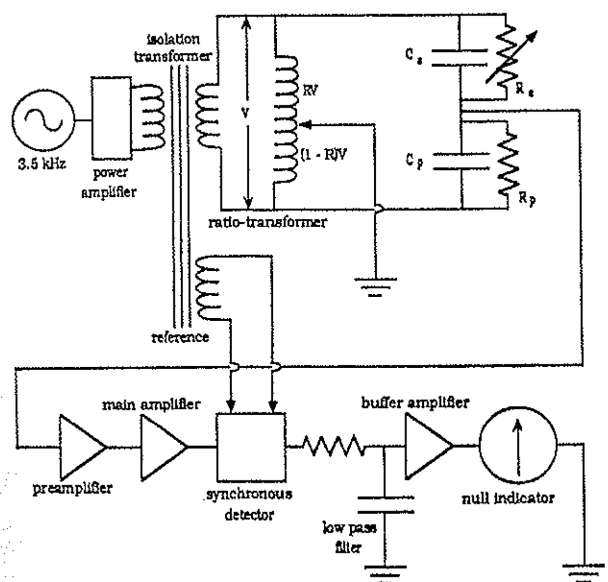

Figure 1
Schematic of the ratio-transformer bridge

R_p represents the leakage resistance of the dust cloud and R_s is a variable resistance which balances the bridge for the out-of-balance (quadrature) signal.

The remaining electronic circuitry follows conventional practice for detecting signals which may be obscured by noise. It uses a synchronous detector which is a specialised AC voltmeter using phase sensitive detection to recover the in-phase low level signals of the same frequency as the driving frequency. Its output is connected to an RC low-pass filter with selectable time constants. This results in a detector with a very narrow bandwidth, typically less than 1Hz, and capable of extracting a signal which is a factor of two orders of magnitude smaller than the noise.

The measurement procedure with the laboratory dust meter requires two observations, namely, an initial measurement with the probe exposed to clean air and one made with the probe immersed in the dispersed dust. The dust concentration is found from the difference between ratio settings (ΔR) multiplied by a calibration factor previously established for the particular coal type (Gillies, Robertson and Oldroyd, 1990).

UNDERGROUND DUST METER

A previous investigation, where tests were undertaken in the rotating dust explosion chamber with a heated wire ignitor (Gillies, Robertson and Oldroyd, 1990), established that airborne coal dust may explode in the concentration range between 10 and 100 g/m^3 in the presence of low concentrations of methane. However, higher concentrations are possible underground so the meter range was designed to cover from 1 to 400 g/m^3 with a target resolution of 10 percent at the lower concentration.

The UQDM can logically be divided into two sections, namely, the capacitance cell with associated analogue circuits and the digital section. A block diagram of the complete system is shown in Figure 2.

The pair of capacitors used in the laboratory probe are not suited for monitoring purposes because small variations of temperature and relative humidity give capacitance changes comparable to those from variations in coal dust concentration in the region of 1 g/m^3. Thus the new probe consists of a pair of nearly identical capacitors sharing a common electrode. The electrode gaps are thermally stabilized and with one capacitor shielded from the dust environment, measurements are insensitive to temperature and relative humidity changes. The dual capacitor assembly has electrode gaps of 5 mm, electrode diameters of 100 mm and guard ring gaps of 1 mm. The capacitance of each unit is 14 pF in air. For intrinsic safety, stainless steel was used for all components except for brass temperature compensating elements.

In the analogue section, improved circuit design in the oscillator and synchronous detector gave a significant

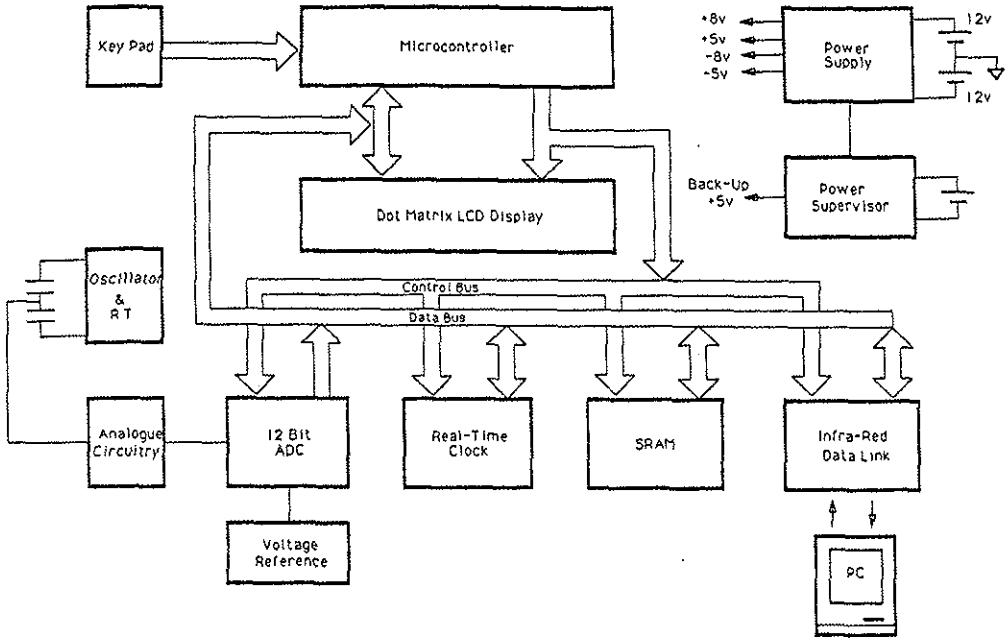

Figure 2
Schematic of the portable dust meter system

increase in signal to noise performance compared to current designs and resulted in the lower limit of dust concentration of 1 g/m^3. The circuit is controlled by a microprocessor in the form of a programmable logic controller with associated peripherals, shown by the various blocks (Figure 2). This allows flexible operating modes for the instrument; each mode is selectable on an alpha-numeric keypad. The microcontroller also enables measurement sequences and other logistic data to be recorded. It facilitates some data processing and displays operating sequences and data on a liquid crystal display. Data is downloaded to a portable computer using an infrared data link. Electronic circuits, electrical components and the mechanical construction were required to meet intrinsic safety requirements.

The coal dust and air mixture is continuously drawn through the electrode gap of one capacitor by a fan mounted below the capacitor assembly. As a consequence, some coal dust accumulates on the surface of the electrodes. This is removed by a compressed air-purge cleaning system. Electrode surfaces are flushed at the start of each measurement cycle by streams of air dispersed from jets located above the entrance of the sensing capacitor. The dispersion duration of about 0.5 seconds is controlled by a solenoid valve that is part of the compressed air system. The airflow between the electrode gaps enhances the removal of the displaced dust.

MINE APPLICATIONS

The high production rates being achieved on Australia's newer longwall faces result in the generation of significant levels of fine coal dust along the face, return airway and in the immediate goaf during collapse. Little is currently known of the total dust levels associated with mining activity in underground workings. Phillips and Landman (1992) undertook a program of sampling in four South African mines which use continuous miners in bord and pillar sections. The investigation used open gravimetric sampling pots and MSA air pumps to collect dust samples of the -600 μm fraction from within 0.1 to 0.4 m of operating cutting picks. Average concentrations for the four mines were 124, 160, 157 and 135 g/m^3. They concluded that, based on the chemical composition of the coal and the presence of methane, the continuous miner drums were capable of dispersing explosible concentrations of coal dust in the poorly ventilated headings.

Besides dust, there may be high rates of methane emission in several Central Queensland operations as mining panels move down-dip. Research has shown that airborne coal dust and methane can act synergistically to form hybrid explosible mixtures, even though each fuel is present in a concentration below its lean limit (Field, 1982; Foniok, 1985). This interaction increases the risk of an explosion underground (Singhal, Stewart and Bacharach, 1987). As mining progresses, airborne dust or settled dust layers cannot readily be inertised by limestone dusting in the vicinity of the face. For safety reasons, the monitoring, evaluation and suppression of airborne coal dust concentrations is therefore a research priority that has been recognized and supported by the industry.

Proposed future projects using the dust meter relate to the potential for coal mine explosions, particularly in longwall mines, and aim at managing risks to minimise causative factors. Evaluation tests are planned for early 1993 at longwall installations in Central Queensland. Dust concentrations along the face and in returns will be systematically monitored. Data will be compared to laboratory results of explosibility tests undertaken in an explosion chamber that examined different seam coals over a range of methane concentrations. From the concentration profiles, suppression strategies will be developed. This approach has not previously been possible because quantified dust levels have not been available.

CONCLUSION

The University of Queensland Dust Meter has the potential of providing contour maps of dust concentration in hazardous regions in underground coal mines. This has not previously been possible. The data will provide the basis for strategies to minimize the risk of mine explosions. The meter has met Australian Intrinsic Safety Standards and underground trials are planned for early 1993.

The dust measurement technique has the potential for use in other areas of the coal industry. For example, with a modified probe measuring conductivity the meter could measure coal slurry concentrations in pipelines. It would also appear to have application to combustion control in the electrical power generation industry by measuring the concentration of pulverised coal feed to the furnace. Preliminary investigations of these applications have been undertaken.

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