APPLICATION OF THE DIESEL DISCRIMINATING FIRE SENSOR TO THE MEASUREMENT OF RESPIRABLE COAL DUST

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Abstract-A novel detector which can distinguish fire smoke from diesel particulates was tested to determine its response to respirable dusts in the concentration range of 0 to 7 mg/m^3. The test results indicated that the detector response was linear over this dust concentration range for respirable coal dusts and non-linear for respirable rock dust. The response to respirable coal dust was also found to vary directly with the volatile fraction of the coal dust. Based upon these results, the use of this detector as a continuous monitor of respirable dust in underground coal mines has significant potential.

I. INTRODUCTION

Measurement of respirable dust in underground coal mines is of significant importance in maintaining a healthful environment for the mine worker. Current practice employs the acquisition of respirable dust on a filter cassette during an eight-hour working shift. The filter cassette is then dried and the mass of dust collected, then measured. The mass of dust measured divided by the total sample volume yields a time-weighted 8-hour average dust concentration. By regulations (30 CFR, Part 70.100) (*1*) this average respirable dust concentration cannot exceed 2.0 mg/m^3. Generally, the filter cassette is contained within a Coal Mine Dust Personal Sample Unit that is worn by mine personnel and continually samples the mine air at a nominal flow rate of 2.0 liters per minute. At the inlet to this unit is a small cyclone that allows only dust that is respirable to flow to the filter cassette. Respirable dust is generally considered to be dust particles with diameters less than 10 μm.

While this method of measurement does provide a valid representation of the miner's exposure to respirable dust levels during a typical work day, it does not provide sufficient information relative to areas in which high dust levels may exist, or the duration of excessive dust levels in these areas. In addition, if areas of high dust levels can be located, then there also exists a need to determine the effectiveness of various techniques to reduce these levels. The current practice is not designed to provide the continuous, or quasi-continuous, information necessary to make these determinations. As a result, there exists a need for a device which can be deployed as a continuous monitor of respirable dust levels at fixed locations or located on mine equipment. The device can be expected to encounter excessive levels of dust, droplets from continuous water sprays, and elevated levels of methane.

Such a device, then, needs to be permissible for use in flammable atmospheres; it must be capable of tolerating excessive levels of dust while remaining operational for periods of days or weeks; and it must be impervious to the presence of water droplets or excessive moisture that can produce significant measurement error. In addition, the device should be insensitive to types of coal dust so that its use is not severely limited.

Certain techniques to develop such a device are the subject of intensive research efforts by the Bureau of Mines. Optical techniques suffer from contamination by moisture, the presence of water droplets, type of coal, and size distribution of the respirable dust. Combined, these effects can produce intolerable measurement errors for an optical device. Continuous gravimetric sampling, such as the use of a device called the Tapered Element Oscillating Microbalance (TEOM)[1], or the measurement of pressure drop across a filter as it collects respirable dust, offer greater potential, but still suffer from the presence of water droplets, excessive moisture, and, to a lesser degree, elevated levels of dust of prolonged duration.

During the past few years, a novel sensor has been developed by the USBM to distinguish between fire smoke and diesel smoke so that early-warning fire detection in diesel-operated mines is not compromised by the combustion products exhausting from diesel engines. A description of this detector and its principle of operation can be found in reference 2. Briefly, the detector capitalizes upon the fact that smoke produced from fires contain a significant volatile fraction while smoke produced from diesel engines contain only a minute (if any) volatile fraction. When volatile smoke particles pass through a small heated chamber called the pyrolysis tube (air temperature ~300 °C), they devolatilize even further producing smaller particles but in much greater number concentrations. Smoke particles from diesel engines are unaffected as they flow through the pyrolysis tube.

Coal dust, like fire smoke, contains a significant volatile fraction, ranging from about 16% to about 40% depending on the type of coal. Even though coal dust is much larger in particle size than fire smoke, it is also known to devolatilize when subjected to temperatures in excess of about 450 °C. However, owing to the larger particle size, the number concentration of respirable dust particles is extremely low. At a mass concentration of respirable dust equal to 2.0 mg/m^3, and a volume mean diameter of 3.0 μm, the concentration on a number basis is only ~110 particles/cm^3. A hypothesis was presented that, upon devolatilization of this dust, the resultant number concentration of smoke particles could possibly increase dramatically to the point where the smoke particle level could be easily measured by the ionization chamber of the detector. If the hypothesis proved correct, then two additional questions needed to be addressed.

First, how does the detector's response vary as a function of respirable dust concentration, and second, how does the detector respond as a function of the volatile fraction of the respirable dust? If the hypothesis proved correct, and if these two questions could be answered, then the potential of this detector for use as a continuous monitor of respirable dust

[1]Reference to specific instruments does not imply endorsement by the U.S. Bureau of Mines.

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could be determined. One benefit is immediately obvious – namely, that operating the pyrolysis tube at temperatures of ~450 °C removes any uncertainty due to water droplets and excessive moisture, a major impediment to other approaches under investigation. Also, previous field tests of the detector indicated that the detector can survive extended periods of continuous operation (3-6 months) before dust contamination within the detector begins to degrade its performance. Consequently, even though prolonged exposure to excessive respirable dust levels could shorten this period, continuous operation for periods of 2 to 6 weeks should be readily obtainable before maintenance and cleaning are warranted.

The operation of the pyrolysis tube at elevated temperatures does pose a problem for operation in flammable atmospheres. However, it should be noted that the component of the detector containing the pyrolysis tube is a separate component that can be made permissible, and that the ionization chamber detectors and associated electronics are intrinsically safe. Further, the ionization chambers use a single radioactive source of Americium 241 with a total activity of 5.0 microcuries, which is the exempt level for this radionuclide.

In order to test the hypothesis discussed above and to answer the two fundamental questions about the detector and its response to respirable dust, a series of tests were devised. These tests and their results are presented in the sections that follow.

II. EXPERIMENTAL

Fig. 1 shows the system used to determine the response of the diesel discriminating detector (DDD) to various concentrations of respirable coal dust. Prior to each series of tests, the dust generating system was adjusted to yield a stable concentration of respirable coal dust within the test chamber (*3*). The instrument used to measure this concentration was a Tapered Element Oscillating Microbalance (TEOM) with a sampling location located 180° from the sampling location of the DDD and at the same height and distance from the wall as the DDD.

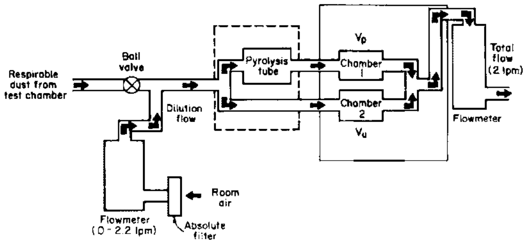

Fig. 1. Schematic of the test configuration used to sample and measure the response of the DDD to levels of respirable dust produced in the aerosol test chamber.

Continuous recordings of the respirable dust concentration, as measured by the TEOM, were obtained for each series of tests. In general, these data indicate remarkably constant levels of dust within the test chamber during the duration of each experiment.

Experiments were conducted using samples of Pittsburgh seam coal and Pocahontas seam coal with volatilities of 36.5% and 17.1%, respectively. Because respirable dust may also include rock dust, tests were also conducted using respirable rock dust. For Pittsburgh seam coal dust, measurements were made over a concentration range from 0 to 7 mg/m^3; for Pocahontas seam coal dust, over the range 0 to 3.6 mg/m^3; and for rock dust, over the range 0 to 3.0 mg/m^3.

During each series of experiments, the valve of fig. 1 was adjusted to dilute the dust entering the pyrolysis tube. With the valve completely closed, the dust flow was shut off and the air entering the pyrolysis tube contained no particles or dust. With the valve completely open, it was found that a small dilution flow was always present, reducing the actual dust concentration entering the pyrolysis tube by about 7%. By adjusting the valve, the dilution factor could be varied continuously from 0 to 0.93, its maximum value. If Q_D is the dilution flow and Q_T is the total flow, then the sample flow is $Q_S = Q_T - Q_D$. The dilution factor, D_f, is defined simply as

$$D_f = \frac{Q_S}{Q_T}, \tag{1}$$

such that the mass of respirable dust entering the pyrolysis tube, M_{PT}, is related to the mass of dust in the test chamber M_{TC}, by the expression

$$M_{PT} = D_f \cdot M_{TC}. \tag{2}$$

III. THEORY

The DDD (see fig. 1) consists of two components. The first component is a small housing that contains a "TEE" connector and the pyrolysis tube. The second component is a larger housing that contains the two ionization chamber detectors, small pump, and electronics. Dust from the test chamber enters the first component where the total flow is split into two separate and equal flows. One flow path goes directly through a short tube to ionization chamber No. 2, while the second flow path goes through the pyrolysis tube to ionization chamber No. 1. The two chambers are identical and share a common source of Americium 241 with an activity level of 5.0 microcuries. By applying a constant voltage to the source electrode, equal ion currents are established in the two ionization chambers which the electronics converts to voltages, V_p, and V_u, corresponding to chambers 1 and 2, respectively.

The response of each measuring ionization chamber is related to the particle diameter, d_o, and number concentration, n_o, of particles within the chamber, via the expression

$$\frac{\Delta V}{V_o} = \frac{V_o - V}{V_o} = 1 - \frac{1}{K_o\, d_o n_o}\,(1 - e^{-K_o d_o n_o}) \tag{3}$$

where K_o is a chamber constant $\cong$ 0.0025 cm^2/p,
d_o is the number mean average particle diameter (in cm),
n_o is the average particle concentration (in p/cm^3),
ΔV represents the voltage decrease, and
V_o represents the starting voltage when no dust or smoke is present.

When no dust or smoke is present, $V_p = V_u = V_o$ = 10.0 volts.

For respirable dust that has not thermally decomposed, the voltage reduction in chamber 2 is negligible, and the unpyrolyzed voltage, V_u, serves as a dynamic reference voltage. The voltage difference, ΔV_T, can then be written as

$$\frac{\Delta V_T}{V_u} = \frac{V_u - V_p}{V_u} = 1 - \frac{1}{K_o d_o n_o}(1 - e^{-K_o d_o n_o}) \qquad (4)$$

where d_o and n_o now represent the number mean average diameter and number concentration of the smoke particle produced from the thermal decomposition of the respirable dust.

For values of $d_o n_o \leq 120$, the product $K_o d_o n_o$ is less than 0.3, and equation 4 can be expanded in a Taylor series to yield

$$\frac{\Delta V_T}{V} \cong \frac{1}{2} K_o d_o n_o. \qquad (5)$$

In the actual device, the response of the detector, V_{DDD}, equals $\frac{1}{5}\Delta V_T$, and since V_u = 10.0 volts,

$$V_{DDD} = K_o d_o n_o. \qquad (6)$$

IV. RESULTS AND ANALYSIS

A. DDD Response

For Pittsburgh seam coal, experiments were conducted at two levels of respirable dust within the test chamber (M_{TC} = 3.8 and 7.1 mg/m^3). The M_{TC} values measured by the TEOM are shown in figs. 2 and 3, for these average dust levels. By varying the dilution factor, D_f, it was possible to span the dust concentration range of $0.87 \leq M_{PT} \leq 6.7$ mg/m^3.

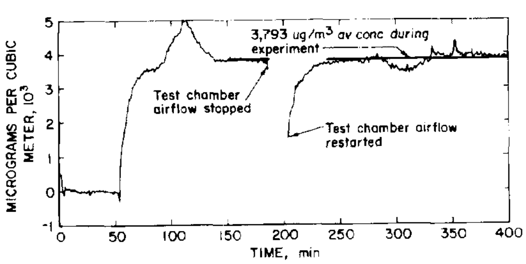

Fig. 2. Respirable dust concentration in the test chamber as measured by the TEOM for Pittsburgh seam coal dust at a nominal concentration of 3.8 mg/m^3.

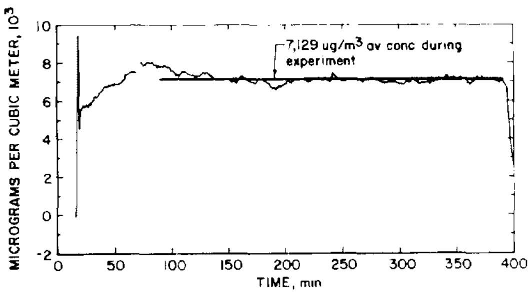

Fig. 3. Respirable dust concentration in the test chamber as measured by the TEOM for Pittsburgh seam coal dust at a nominal concentration of 7.1 mg/m^3.

For the Pocahontas seam coal, measurements were made at values of M_{PT} between 0.82 and 3.6 mg/m^3. And for rock dust, measurements were made at values of M_{PT} between 0.8 and 3.0 mg/m^3. The response of the DDD to each of these dusts is shown in fig. 4.

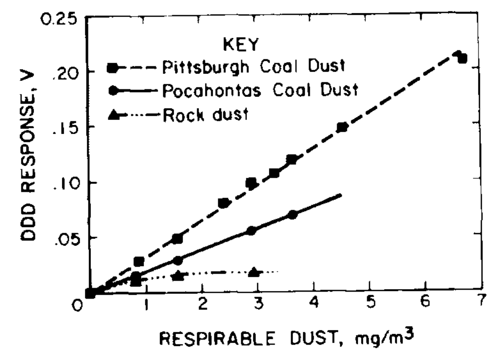

Fig. 4. Measured response of the DDD to concentrations of Pittsburgh seam coal dust, Pocahontas seam coal dust, and rock dust.

For Pittsburgh seam coal, the measured response was found to vary linearly with mass concentration according to

$$(V_{DDD})_{PGH} = 0.032\, M_{PT}. \qquad (7)$$

For Pocahontas seam coal, the measured response also varied linearly, but with a reduced sensitivity due to its lower volatility, according to

$$(V_{DDD})_{POCA} = 0.019\, M_{PT}. \qquad (8)$$

For rock dust, the measured response was found to vary in a non-linear fashion according to

$$(V_{DDD})_{RD} = 0.018(1 - e^{-1.37 M_{PT}}). \qquad (9)$$

Even though rock dust is considered to be an inert dust, it does devolatilize but at a much slower rate than coal dusts (*4*). Because of this, the detector response to respirable rock dust is not surprising.

The relative responses of the DDD to Pittsburgh and Pocahontas coal dusts do not scale directly with the volatilities from proximate analyses of the dusts. However, data obtained by Hertzberg (5), et al. for these two coals under conditions of very rapid heating by a CO_2 laser, yield volatilities of 57% and 34% for Pittsburgh and Pocahontas dusts respectively. If these two values are used, then the relative responses scale directly with these values. Assuming such a relationship to be valid over a range of volatilities, then the following general expression results:

$$V_{DDD} = 0.056\, f_v \cdot M, \qquad (10)$$

where f_v is the laser volatile fraction, and M is the respirable dust concentration, in mg/m^3.

B. Reproducibility and Noise

It should be noted that the data of fig. 4 actually represent the average of at least 4 measurements at each dust concentration, and, in some cases, as many as 16 individual measurements. For Pittsburgh seam coal dust, the maximum deviation of any individual measurement from the response given by equation 7 was $\pm 9.2\%$. For Pocahontas seam coal dust, the maximum deviation of any individual measurement from the response given by equation 8 was $\pm 5.2\%$. For rock dust, the maximum deviation of any individual measurement from the response given from equation 9 was $\pm 11.6\%$. These values represent the maximum deviations, and the average deviations were found to be less than one-half these values. These data would indicate that the measurements for a particular dust are quite uniform and reproducible.

During the experiments, the inherent noise of the detector was measured to be ± 0.003 volts. Using equation 7, 8, and 9, the equivalent dust noise levels are found to be ± 0.094, ± 0.158, and ± 0.133 mg/m^3, respectively.

C. Impact of Rock Dust

In any real application, the detector will encounter mixtures of coal dust and rock dust, and as a result, the question naturally arises as to the meaning of the detector's response under these conditions. Clearly, it is not possible to separate the two dusts using this detector. Now, since the detector is less sensitive to rock dust than to coal dust, the presence of significant levels of rock dust would not contribute very much to the detector's response. If the detector response is assumed to always be that for pure coal dust, then the question becomes one of what fraction of rock dust would begin to introduce significant error in the measurement.

The Mine Safety and Health Administration has indicated that any continuous monitor of respirable mine dusts shall be capable of indicating the actual level to within $\pm 25\%$. If the detector response is based upon the assumption of pure coal dust, then at what level of rock dust does the indicated level read less than 75% of the actual level present?

If f_r represents the mass fraction of the total dust that is rock dust, then the detector response to mixtures of Pittsburgh seam coal dust/rock dust can be estimated by combining equations 7 and 9. Similarly, the detector response to mixtures of Pocahontas seam coal dust/rock dust can be determined by combining equations 8 and 9. The mass fraction of rock dust at which the indicated respirable dust level is less than 75% of the actual value can then be determined as functions of the total respirable dust. The results are shown in fig. 5.

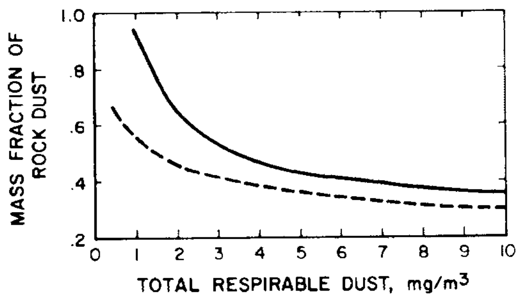

Fig. 5. Estimated mass fractions of rock dust in coal dust/rock dust mixtures necessary to introduce a measurement error greater than 25% for Pittsburgh coal (solid curve) and Pocahontas coal (dashed curve).

For total respirable dust levels up to 10 mg/m^3, the mass fraction of rock dust that could be present and still allow for a maximum uncertainty of 25% exceeds 0.30. For total respirable dust equal to 2 mg/m^3, rock dust could account for 45% of the total mass in a mixture with Pocahontas seam coal dust and 64% of the total mass in a mixture of Pittsburgh seam coal dust. Typical fractions of rock dust found in respirable dust samples rarely exceed 0.30, and are more typically in the range of 0.15 to 0.20. Although these estimates need verification, there is the clear indication that the detector response is not seriously degraded by the presence of rock dust.

D. Comparison With Theory

Now, equation 6 indicates that, theoretically, the response of the detector should vary linearly with the product of the diameter and concentration of the smoke particles produced during the devolatilization of the coal dust. Experimentally, it is found that the response varies linearly with dust mass concentration and laser volatility of the coal dust according to equation 10. Setting the two expressions equal yields the effective smoke diameter-concentration product produced during the devolatilization of coal dust, or

$$(d_o n_o)_{SMOKE} = 22.4\, f_v M. \qquad (11)$$

Equation 11 represents the effective smoke yield in terms of the diameter-concentration product of the smoke.

V. PYROLYSIS TUBE

All of the data were obtained at a total pyrolysis tube power level of 33.5 watts (20 volts and 1.675 amperes). This operating point was chosen arbitrarily and does not necessarily reflect the minimum power levels required for the pyrolysis of respirable coal dust. The pyrolysis tube consisted of 0.008 inch Nichrome 60 wire wound onto a ceramic rod and sealed in a hollow Pyrex glass rod. This coil/rod element was then inserted into the air space of a tube made by joining two brass Swagelok elbow fittings.

The inside diameter for this tube was 20 mm, its length 60 mm, and total volume 1.885×10^4 mm^3. The volume of the air space is this total volume less the volume of the coil/rod element (424 mm^3), or 1.843×10^4 mm^3 (18.43 cm^3). The flow through the tube is one-half the total flow, or 16.67 cm^3/s. Dividing the air volume by the flow yields the residence time of the dust within the pyrolysis tube, or t_{RES} = 1.105 s.

Assuming that the heat flow is radial from the surface of the Nichrome coil, and that the surface temperature of this coil may be calculated from the known current and voltage applied to the coil, then the average radiant flux and air temperature are calculated to be 4.8 watts/cm^2, and 490 °C, respectively, within this air space.

Hertzberg (*6*) has shown that the characteristic time for a coal dust particle to devolatilize decreases as the coal dust particle diameter decreases when the particle is subjected to a constant level of radiant flux. If it is assumed that the maximum respirable coal dust particle diameter is 10 μm, then at an average radiant flux of 4.8 watts/cm^2, the characteristic time to devolatilize is ~0.55 s. For smaller coal dust particles, the time is less. Consequently, for the pyrolysis tube, the residence time of dust particles within the tube must be greater than 0.55 s. The value obtained above is twice this minimum value. Coal is also found to undergo rapid devolatilization when subjected to air temperatures in excess of 450 °C. The average value obtained above is 490 °C. In reality, the devolatilization is probably some complex function of both the radiative flux heating and the convective flux heating at an elevated temperature. For the current experiments, the conditions within the pyrolysis tube are sufficient to satisfy constraints of either type of rapid devolatilization.

However, additional research needs to be done to determine the minimum temperature and radiant fluxes within the pyrolysis tube in order to effect the rapid devolatilization process. Minimizing the level of power consumption is important in order to address the problems of electrical power necessary for the detector to function and of permissibility for use of the detector in flammable gaseous environments.

It is worth noting that for diesel particulate matter, the temperature at which devolatilization occurs is 550 °C, considerably greater than the average temperature of 490 °C of the pyrolysis tube. Although experiments were not conducted using this pyrolysis tube to determine its effect on diesel particulate matter, it is expected that the diesel particulates would not significantly devolatilize. Additional research needs to be done to verify this aspect of the detector operation.

VI. CONCLUSIONS

The data obtained for the response of a diesel discriminating fire sensor to levels of respirable coal dust up to 6.7 mg/m^3 indicate a linear response with mass concentration and laser volatility fractions of the dust. For respirable rock dust, the response was found to be non-linear due to the fact that rock dust is much slower to devolatilize then coal dust. Using the estimated combined response of the detector to mixtures of coal dust/rock dust, mass fractions of rock dust in excess of 0.3 would not seriously degrade the performance of the detector. But additional testing needs to be done to verify these estimates. Although there is clearly a need for further research to refine the detector and its practical application, the data presented in this report indicate that the detector has potential for use as a continuous monitor of respirable dust in underground coal mines.

VII. REFERENCES

1. Title 30, Code of Federal Regulations, Part 70.100, p. 487, 1993.

2. Litton, Charles D. Diesel Discriminating Fire Sensor. USBM IC 9206, 1988, pp. 28-32.

3. Marple, V. A., and K. L. Rubow. An Aerosol Chamber for Instrument Evaluation and Calibration. Am. Ind. Hyg. Assoc. J., v. 44, 1983, pp. 361-367.

4. Hertzberg, M., K. L. Cashdollar, I. Zlochower, and D. L. Ng. Inhibition and Extinction of Explosions in Heterogenous Mixtures. Proceedings of Twentieth Symposium (International) on Combustion. The Combustion Institute, Pgh., PA., 1984, pp. 1691-1700.

5. Hertzberg, M. and I. Zlochower. Devolatilization Rates and Intraparticle Wave Structures During the Combustion of Pulverized Coals and Polymethylmethacrylate. Proceedings of 23rd Symposium (International) on Combustion, The Combustion Institute, Pgh., PA, 1990, pp 1247-1255.

6. Hertzberg, M., I. Zlochower, and J. C. Edwards. Coal Particle Pyrolysis Mechanisms and Temperatures. USBM RI 9169, 1988, 39 pp.

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