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New Laboratory Measurement Method for Water Spray Dust Control Effectiveness

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An innovative method for measuring dust reduction is presented. The approach involves measuring dust as it is introduced into a well-mixed chamber instead of into a tunnel. The technique is equivalent to measuring the product of airflow and dust reduction efficiency of scrubbers, filters and electrostatic precipitators; it is especially convenient in evaluating the effectiveness of open water sprays. The method, which monitors the decay of dust concentration and is useful for both charged and uncharged water sprays, promises numerous benefits including the following: 1) Steady dust production is not required; 2) Only single-point dust sampling is necessary; and 3) Only relative dust concentration accuracy is required. Laboratories engaged in dust control development for mines and mills are encouraged to consider adapting the measurement method for evaluating open sprays. A suitable mixed chamber can be designed, constructed and operated with much less effort than a two-phase tunnel. Data for the dust reduction effectiveness of hydraulic and charged water sprays as well as a water-powered scrubber are presented.

Introduction

The U.S. Bureau of Mines (USBM) sponsored Foster-Miller, Inc., to engage in a series of laboratory and in-mine tests directed toward reducing worker exposure to unhealthful dust concentrations. United States coal mine dust regulations are based on respirable dust (defined as the dust that penetrates a 10-mm nylon cyclone) in the breathing zone of exposed workers. Strategies for dust control are to remove dust from the atmosphere (dust removal) or to modify airflow patterns to position workers in cleaner air (dust avoidance). Water sprays are effective for both strategies. Water spray droplets clean dust particles from the atmosphere and, through momentum exchange, effectively move air to promote dust stratification for dust avoidance.(1) Obviously, sprays are more desirable than electric fans for movement of local air in explosive mine atmospheres.

Walton and Woolcock(2) as well as Cheng(3) have successfully used two-phase wind tunnels to investigate dust removal. Jones(4) has used a two-phase tunnel to investigate dust removal and water spray air moving. In performing spray effectiveness tests in tunnels, the size of the spray relative to the size of the tunnel is important: spray cones so large that droplets impinge on the walls at high velocity do not remove as much dust as those sprays which operate without wall impingement; spray cones so small that the entire cross-section of the tunnel is not acted on raise questions about the effects because of some degree of dust stratification within the tunnel. Additionally, tunnel tests require a reasonably constant dust source, methods for assuring a minimum of dust stratification and representative upstream and downstream dust sampling. Techniques exist to satisfy all of these requirements, but they can be costly and tedious. To circumvent both cost and tedium, a new approach was sought.

The new approach is based on dust removal within a well-mixed chamber. The advantages of this method follow:

- steady dust production is not required;
- only single-point dust sampling is required (a virtually continuous monitor is desirable, however);

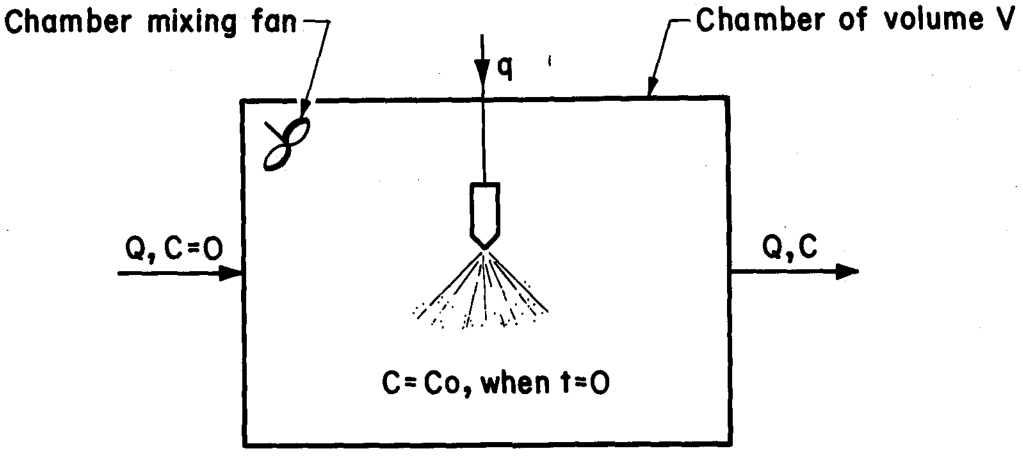

Figure 1 — Test chamber.

TABLE I
Nomenclature

C - dust concentration

C_0 - initial dust concentration

f_i - dust cleaning (volume flow units)

$F - \sum_{i=1}^{r} f_i$

ΔF - f for the scrubbing spray

M - total dust mass = CV

P - water pressure

q - water spray flow

Q - ventilation flow through test chamber

Q' - ventilation flow through spray

t - time

$R - \frac{-\ln C/C_0}{t}$, test decay rate of dust

V - volume of chamber

η - dust reduction efficiency

- only relative, not absolute, dust concentration accuracy is required.

Theory of Measurement

Consider the process in Figure 1. A well-mixed chamber is ventilated in a steady-state manner (steady flow can be zero, as was the case for many measurements). Dust is introduced into the chamber in any convenient way. While the spray or other dust removal device is operated, the concentration decay is monitored as a function of time. Dust concentration is reduced primarily by the following mechanisms:

- scrubbing of the water spray;
- sedimentation due to gravity;
- dilution due to ventilation of clean air;
- Brownian and turbulent diffusion with inertial impaction to chamber surfaces;
- electrostatic forces;
- autocoagulation.

Except for autocoagulation, these concentration reduction effects are linear with respect to dust concentration; that is, the rate is dependent on the instantaneous concentration. Autocoagulation is a second-order removal mechanism with a very slow removal rate except for very dense aerosols. Since dust clouds of interest here are very much less dense, this analysis considers only linear dust removal mechanisms.

Referring to the process in Figure 1 and the nomenclature in Table I, conservation of mass requires that

$$\frac{dM}{dt} = V\frac{dC}{dt} = -C(Q + f_1 + f_2 + \ldots + f_n)$$

or

$$V\frac{dC}{dt} = -C(Q + F).$$

By rearrangement, this differential equation can be directly integrated. For decay, let the limits be $C = C_0$ when $t = 0$ and $C = C$ when $t = t$. With algebra, the solution is

$$\frac{\ln \frac{C}{C_0}}{t} = -(Q/V + F/V).$$

This expression is the log-slope of the dust concentration decay curve. The term Q/V is the decay rate due to flushing or ventilating the chamber. Clean ventilation air may be thought of as diluting the dust. The F/V term is the lumped sum of linear removal mechanisms.

A linear mechanism can be easily isolated through experiment. For example, the effect of the water spray for removing dust may be isolated from other removal effects. Consider a set of experiments at constant ventilation where

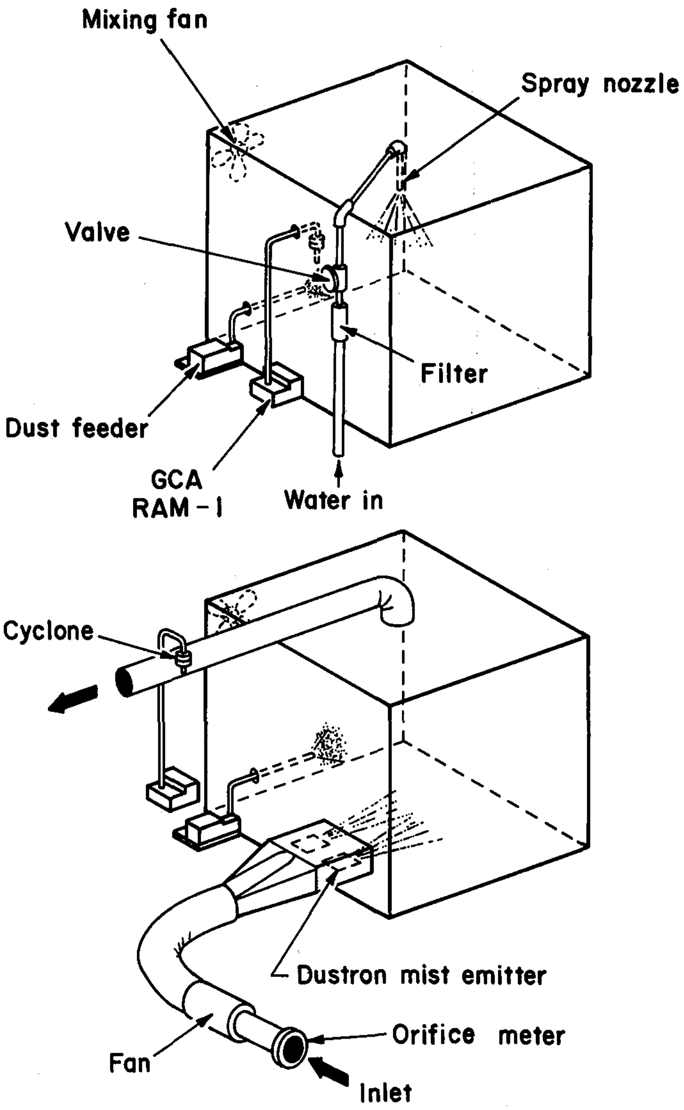

Figure 2 — Static chamber for hydraulic spray tests (top); flow-through chamber for charged spray tests (bottom).

a) The decay of dust concentration with application of charged spray is measured.
b) The decay of dust concentration without spray is measured.

In the first case:

$$R = \frac{Q + F}{V};$$

while in the second case

$$R' = \frac{Q + F'}{V}.$$

Take the difference:

$$R - R' = \Delta R$$

$$\Delta R = \frac{F - F'}{V} = \frac{\Delta F}{V}$$

This is the rate of dust removal due to only the spray. If the ratio C/C_0 is plotted on semi-log paper against time, ΔR is the negative of the slope; that is, $(\ln C/C_0)/t = -\Delta R$. The term $-V\Delta R$ is the dust cleaning of the spray in volumetric flow units, *e.g.*, m^3/s. Physically this may be thought of as the operation of an equivalent scrubber, filter, *etc.*, operating within the chamber with an effective dust removal efficiency η and effective pass-through flow rate Q', *i.e.*, $-V\Delta R = \eta Q'$. From external measurements of concentration *vs.* time, the product $\eta Q'$ can be determined.

For open sprays in workspaces, $\eta Q'$ is the fundamental parameter determining dust control effectiveness. A scrubber or filter, *etc.*, with a very high efficiency and low flowrate may not be as valuable as a similar device with higher flowrate but lower efficiency. The $\eta Q'$ product from each collector must be compared to determine the most effective system for removing dust when evaluating dust collectors.

Water may be a scarce, valuable commodity, or its use may be restricted to minimize adverse effects on product or equipment. For this reason, spray dust control effectiveness should be normalized for water usage; that is, $\eta Q'/q$. Using q in the same units as Q' provides a unitless factor-of-merit that allows international comparisons without unit conversions.

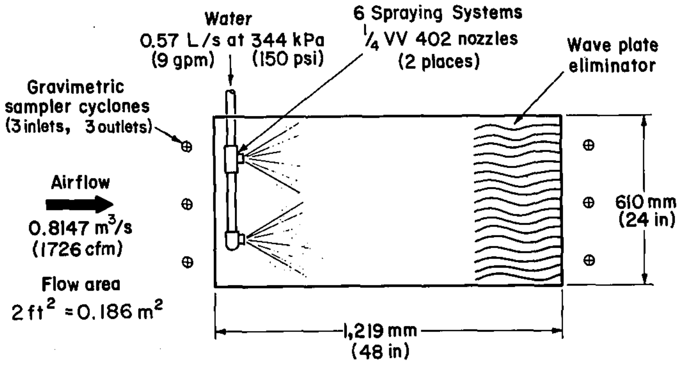

Figure 3 — Water-powered scrubber.

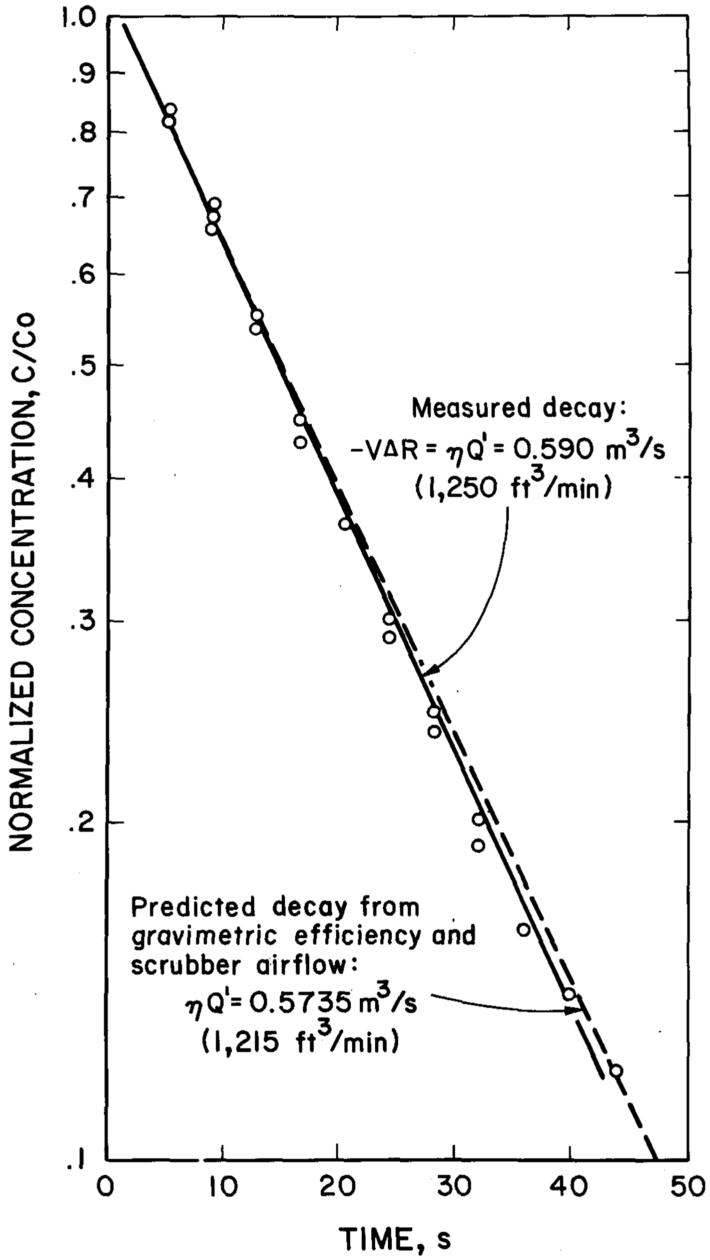

Figure 4 — Dust concentration decay curve for water-powered scrubber in static chamber.

This analysis treats the dust as monodispersed; that is, no account is made for variations in dust particle size. The respirable dust fraction tends to be close enough to monodispersed behavior for practical work. In any case, the effects of this restriction may be checked experimentally. This analysis predicts, in the absence of dust production within the chamber, that any dust concentration will have a log-linear or exponential time decay curve. Experimentally, this is checked by plotting the logarithm of concentration, corrected for any background concentration, against time. If the curve is linear, then effects due to nonlinear dust reduction and polydispersed aerosols may be ignored.

Experiments

The experimental chamber was constructed of plywood in the approximate shape of a cube about 2283 mm (7.49 ft) on

TABLE II
Dust Removal Performance for Various Hydraulic Spray Nozzles

Spray Nozzle		$\eta Q'/P^{1.08}$		$\eta Q'/P^{1.08}q$		Pressure Range		Nominal Spray Angle (deg)	Spray Type
		$\frac{m^3}{s\text{-}(kPa)^{1.08}}$	$\frac{ft^3}{min\text{-}(psi)^{1.08}}$	$(kPa)^{-1.08}$	$\frac{ft^3}{gal\text{-}(psi)^{1.08}}$	MPa	(psi)		
Spraying Systems	BD 3-3	1.7×10^{-5}	(0.292)	0.20	(0.22)	≤ 1.39	(≤ 200)	79	Hollow-cone
Spraying Systems	BD 5-5	2.16×10^{-5}	(0.368)	0.12	(0.13)	≤ 1.39	(≤ 200)	76	Hollow-cone
Spraying Systems	BD 8-1	1.50×10^{-5}	(0.256)	0.19	(0.20)	≤ 6.89	(≤ 1000)	42	Hollow-cone
Spraying Systems	BD 8-2	2.18×10^{-5}	(0.372)	0.20	(0.22)	≤ 6.89	(≤ 1000)	56	Hollow-cone
Spraying Systems	BD 10-10	3.71×10^{-5}	(0.632)	0.13	(0.14)	≤ 1.39	(≤ 200)	72	Hollow-cone
Spraying Systems	BD 20-2	2.29×10^{-5}	(0.390)	0.16	(0.17)	≤ 1.39	(≤ 200)	33	Hollow-cone
Spraying Systems	1/8 GG3	1.36×10^{-5}	(0.232)	0.18	(0.19)	≤ 1.39	(≤ 200)	53	Solid-cone
Spraying Systems	1/4 GG3	1.73×10^{-5}	(0.295)	0.18	(0.19)	≤ 6.89	(≤ 1000)	53	Solid-cone
Spraying Systems	GG3009	1.77×10^{-5}	(0.302)	0.12	(0.13)	≤ 1.39	(≤ 200)	23	Solid-cone
Bete	L54	2.11×10^{-5}	(0.359)	0.19	(0.20)	≤ 1.39	(≤ 200)	Not avail.	Atomized
Bete	L66	2.68×10^{-5}	(0.457)	0.16	(0.17)	≤ 1.39	(≤ 200)	Not avail.	Atomized
Spraying Systems	H1/4 VV6506	2.29×10^{-5}	(0.391)	0.25	(0.27)	≤ 6.89	(≤ 1000)	75	Flat fan
Spraying Systems	H1/4 VV9506	2.37×10^{-5}	(0.404)	0.24	(0.26)	≤ 6.89	(≤ 1000)	106	Flat fan
USS	PD 1746	1.99×10^{-5}	(0.339)	0.19	(0.21)	≤ 6.89	(≤ 1000)	Not applic.	Shrouded
Deron	070	0.22×10^{-5}	(0.038)	0.02	(0.02)	≤ 1.39	(≤ 200)	Not applic.	Shrouded

edge [11.9 m^3 (420 ft^3)]. Internal surfaces were lined with thin polyethylene sheets for waterproofing and with aluminum screening to form an electrically grounded surface. A drain was installed in the floor. Water pressures to 6.89 MPa (1000 psi) could be supplied. Provisions for measuring water pressure and flow were made. A mixing fan was installed which sufficiently homogenized dust concentrations as determined empirically. A fan supplied air through a duct with an orifice meter for airflow measurement. Dust concentrations were measured with a GCA Corporation RAM-1 aerosol monitor. Sampling was through a 10 mm nylon cyclone so that only the respirable fraction of dust was measured. Water sprays alone produced no significant readings on this apparatus. Figure 2 shows the chamber as set up for two types of tests — for pure hydraulic sprays and for electrostatically charged mists.

The test dust was fine Arizona road dust and was pneumatically transported into the chamber from a continuous but imprecise dust feeder. Sufficient dust was injected to produce an upscale value on the aerosol monitor. The feeder was then stopped, and the dust concentration was allowed to decay.

When a convenient value of dust concentration was reached during decay, the recording of dust concentration as a function of time began. In some cases, "background" dust concentrations in the ambient air relative to test values were significant. In these cases, the background value was subtracted from all measured values. Calculations were made using the ratio of the net concentration values.

Test of a Water-Powered Scrubber

Agreement of results from a new method with those from existing methods is a test of any new method. An opportunity to check agreement arose with a need for measuring performance of an enclosed water-powered scrubber. Figure 3 shows a schematic of the scrubber. Air is induced into the scrubber by the air moving action of the 12 water sprays. Dust within the induced air is scrubbed while passing through the sprays. Wave plates on the downstream end remove virtually all water mist. This scrubber allows conventional measurement of dust reduction efficiency (η) across the scrubber and airflow (Q') through the scrubber. These measurements can be used to predict the dust reduction rate within the chamber, thus providing a validation test for the new chamber method.

Figure 4 shows the concentration decay for this scrubber operating within the chamber with no ventilation flow, Q, through the chamber. The concentration decay is for dust particles which penetrate a 10 mm nylon cyclone with a 2 Lpm flow rate. The apparent log-linear decay justifies treating the dust fraction as virtually monodispersed. Shown with the measured decay is the predicted decay, which is based on scrubber dust removal efficiencies measured directly during the test. Three gravimetric samplers with 10 mm nylon cyclones at 2 Lpm determined dust concentration at the inlet and the outlet of the scrubber. Dust removal efficiency was thus determined to be 70.4%. Airflow through the scrubber was determined to be 0.815 m^3/s (1730 cfm), using a velocity traverse at the outlet. The product of these values, $\eta Q'$, is 0.573 m^3/s (1215 ft^3/min).

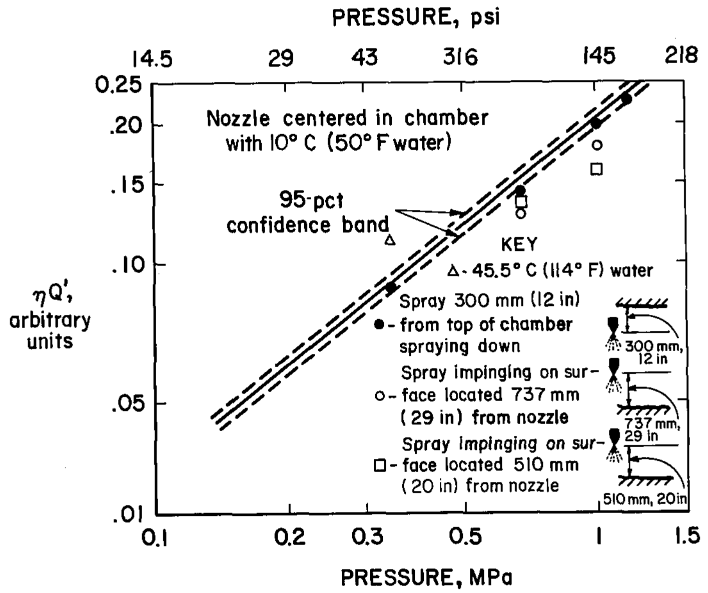

Figure 5 — Effect of temperature and surface impingement on the effectiveness of a BD3-3 nozzle.

The dust decay rate with the scrubber turned off was negligible compared to the decay rate while operating; hence, the value of ΔR is as shown in Figure 4. Using the rates shown and the volume of the chamber, a value of $\eta Q' = 0.590\ m^3/s$ ($1250\ ft^3/min$) is calculated. This is about 3% larger than predicted by gravimetric and flow measurements. Such excellent agreement — well within the cumulative error expected from errors possible because of the several measurements involved — provides confidence that the new method is also applicable to open sprays, which cannot be as easily measured by conventional methods.

Hydraulic Spray Tests

Many commercially available spray nozzles were tested. Nozzles were located in the center of the chamber. With no ventilation flow, test procedures were similar to the test of the water-powered scrubber, although initial concentrations were lower — about 130 mg/m^3. Unlike the scrubber, separate values for airflow through the spray Q' and dust removal efficiency could not be measured. Indeed the practical problems of making these measurements argue strongly for using the chamber method.

For many measurements, concentration decay rates of dust alone, in the absence of the spray, were smaller than the sprays but still significant. This required calculating ΔR from measuring R before turning on the spray, then from R' after the spray was turned on. Also, a slight curvature of the semi-log decay curves can be observed. This may be caused by the larger particles being removed more efficiently than the smaller particles, thus causing the particle size distribution to be shifted to smaller sizes with time. The remaining smaller particles are expected to be removed at a slower rate owing to their reduced removal efficiency.(2) In spite of this observed curvature, a significantly large initial segment could be identified where a log-linear curve could be fit with high fidelity. This segment was used in calculating $\eta Q'$ for the test.

For a given spray nozzle, $\eta Q'$ (unnormalized for water usage) increased approximately in proportion to water pressure P. Close data examination, however, shows that $\eta Q'$ increases slightly faster than $P^{1.0}$, with $P^{1.08}$ producing an excellent empirical fit. We believe this to be reasonable based on independent experience. In a set of air moving tests carried out in a wind tunnel under constant geometry, we found the induced air movement, Q', varied as $P^{0.75}$. The spray capture cross section, related to η, goes as q/D_{32}, where D_{32} is the Sauter mean (volume/surface) droplet diameter.(5) Work by Dundas(6) indicates that $D_{32} \propto P^{0.33}$. The implication is that $\eta Q'$ is likely to be proportional to $P^{1.08}$, which was found empirically. Further proof of this is an area for future research.

Table II shows results for 15 spray nozzles presented in the form of $\eta Q'/P^{1.08}$ and normalized for water usage as $\eta Q'/P^{1.08}q$. In both cases, the higher the value, the higher the dust removal rate. A caveat exists for applying these values to open work space. Where dust is stratified either vertically or horizontally, the air induced by the spray may be relatively clean. This will produce a lower dust removal rate than expected. Also, we found that values of $\eta Q'$ in Table II correlated directly with air moving ability of the nozzle, as determined by air moving tests in a wind tunnel.

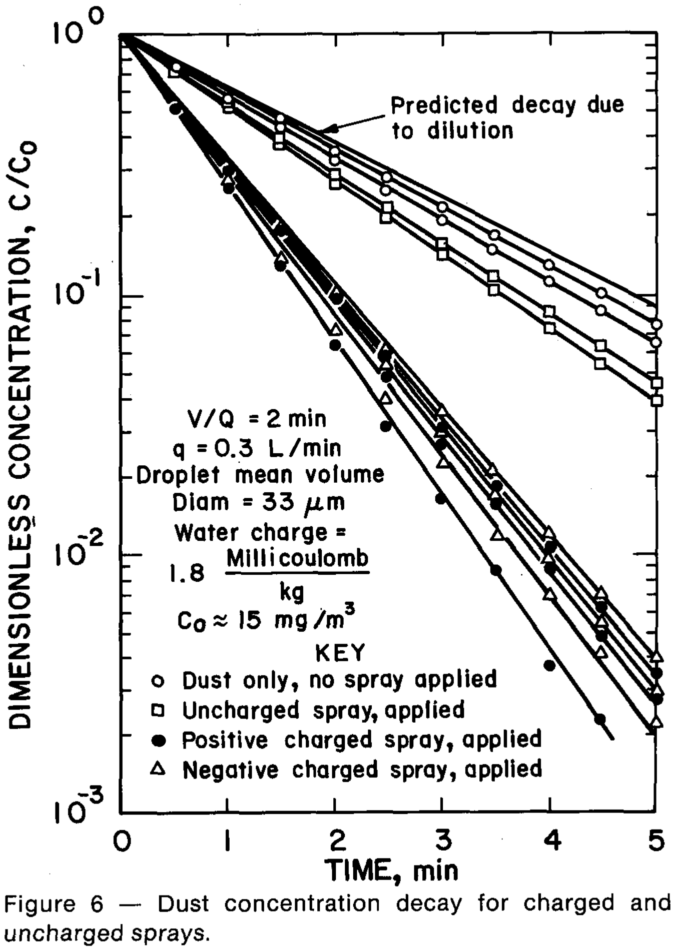

Figure 6 — Dust concentration decay for charged and uncharged sprays.

Factors Influencing Dust Reduction of Hydraulic Sprays

The test chamber provided an excellent vehicle for assessing various influences on dust reduction, including water temperature, addition of wetting agent and proximity to solid surfaces placed in the spray or behind the nozzle. Figure 5 shows the results of tests on a Spraying Systems BD3-3 nozzle. The curve shows the operation of a BD3-3 nozzle at ≤1.39 MPa (200 psi), using 10°C (50°F) water, with a 95% confidence band. Warm water at 45.5°C (114°F) shows improved dust removal. Surfaces located near the spray (upstream and downstream) appear to decrease dust removal slightly. This is likely due to the influence of the surfaces altering the airflow field around the spray, producing a lower Q′ than for a free spray. This slight influence permits operation of spray nozzles as close as 510 mm (20 in.) to surfaces with little performance decrease. This can be important when water sprays are located on mining machinery for dust removal.

Charged Spray Tests

In the course of evaluating charged water sprays for dust control, we tested a Dustron spray unit made by Keystone Dynamic, Inc. Droplets produced from a grounded, conventional, pneumatically atomizing spray nozzle are charged by electrostatic induction. The character of charged spray dust removal differs from that of hydraulic sprays. Dust is removed in hydraulic spray primarily during the very short time it takes for droplets to approach the velocity of the air (stopping time). Charged droplets exert dust removal forces over periods of time many orders of magnitude longer. For this reason, it is important with charged spray to be able to control and vary the contact time between the dust cloud and charged droplet cloud. Airflow through the mixed chamber proved convenient for controlling contact time. Flow Q may be easily varied to control residence time only. In a two-phase tunnel, flow velocity or exposure length must be varied to change residence time. Either variation affects other test conditions, such as turbulent diffusion and wall deposition area. These undesirable changes are avoided with the chamber method.

Figure 6 shows the results gathered from less than half-day testing periods. Pneumatically atomized sprays, both charged and uncharged, were tested. Data clearly show that while the uncharged spray increased dust removal, the charged spray was a significantly better dust remover. For the charged spray, $\eta Q'/q$ is about 40×10^3 (unitless); for the uncharged spray, it is only 15×10^3. These values, which are normalized for water usage, are both higher than any measured during other tests for sprays atomized hydraulically. The small air-atomized droplets are suspected of producing a rate for uncharged spray that is higher than the hydraulic rate for uncharged spray; however, the significantly greater water usage with the hydraulic sprays produced much higher absolute dust removal rates.

The chamber method readily accommodates testing of charged spray. Considerable amounts of data were gathered quickly, thus providing insight into applications of charged sprays. Particularly, residence times must be long; hence, charged sprays are appropriate where ventilation velocities are very low and the need to limit water usage is great. Also, we observed electric field strengths near the breakdown point (spark point) of air due to the electric charge on the cloud. For safety, charge spray application must be limited to nonexplosive atmospheres.

Conclusions

The mixed chamber proved valuable for measuring dust removal effectiveness. This technique is applicable to many dust removal devices such as scrubbers, filters and electrostatic precipitators; however, the advantage is most obvious for open sprays. Our impression is that a suitable chamber can be designed, constructed and operated with much less effort than a two-phase test tunnel.

By employing this method, many properties of open sprays were efficiently determined. Hydraulic sprays were found to have a dust removal effectiveness that is closely proportional to water pressure. A slight increase in effectiveness was observed with warmer water. Only a slight decrease in effectiveness was observed when the spray impinged on surfaces as close as 300 mm (12 in) from the nozzle. A wetting agent added to the spray water did not change effectiveness. Application of electric charge to water droplets produced increased dust removal over uncharged droplets. However, long interaction times between the droplets cloud and dust cloud are necessary.

Laboratories engaged in dust control development for mines and mills are encouraged to consider adapting this measurement method for evaluating open sprays. With the exception of a continuous dust monitor, all equipment may be constructed from low-cost locally available materials.

Acknowledgements

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