Development of a lower-pressure water-powered spot scrubber for mining applications

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Abstract

Water sprays and water-powered scrubbers have both been utilized in the mining and milling industry to suppress airborne dust. Unconfined water sprays operated at lower water pressures of $\leq$*689 kPa (*$\leq$*100 psig) can be very effective at wetting the mine product at the dust source and significantly reducing the amount of respirable dust that becomes airborne. However, unconfined waters sprays can be somewhat ineffective in actually removing airborne dust from the air. On the other hand, water-powered scrubbers operating at higher water pressures of* $\geq$*1,724 kPa (*$\geq$*250 psig) in physical enclosures or ducts have previously been demonstrated to be very effective in removing airborne dust from the air. These higher operating water pressures are uncommon in many mines and mills, so their use is limited. The National Institute for Occupational Safety and Health (NIOSH) recently investigated the performance of a lower-pressure, water-powered inline series spray scrubber for removing localized airborne dust emitted at the source. Results showed noticeable improvements in airborne dust capture efficiency through the operation of multiple inline series hollow cone spray nozzles within a round duct or pipe at the same water pressure as a single spray. Operating hollow cone spray(s) at higher water pressures noticeably improved airflow through the scrubber and yielded some additional scrubber efficiency improvements. Thus, in-line spray scrubber efficiency trade-offs were observed to be made by altering spray power components of water pressure and/or quantity (number of sprays). Results show that, on average, up to 0.23 and 0.32* m^3/s *(484 and 679 cu ft per min) of airflow at 0.81 and 0.69 dust capture efficiencies can be achieved with three 81° and 33° hollow cone inline series sprays, respectively, operating at 1,655 kPa (240 psig).*

Introduction

Water spray systems that were previously developed for creating localized ventilation patterns (shearer clearer, underboom tuned spray system, etc.) and for providing dust suppression (internal stageloader-crusher spray systems, drum sprays, underboom sprays, belt wetting sprays, etc.) have made significant contributions toward successfully reducing the average dust concentration for underground coal miners, reducing these averages from more than 6 mg/m^3 in 1969 to below 2 mg/m^3 today (NIOSH, 1995). However, the former U.S. Bureau of Mines identified a point of diminishing returns for existing mine spray systems operating at higher supply parameters (pressure and quantity) (Schroeder et al., 1986; Colinet et al., 1991) and indicated that these spray systems are probably not adequately providing the silica dust control needed for obtaining lower permissible exposure levels (Organiscak et al., 1990).

The Federal Mine Safety and Health Administration's (MSHA's) dust compliance data (both inspector and operator samples) for permissible exposure limits (PELs) or reduced dust standards due to quartz indicate that a notable portion of the airborne respirable dust samples collected in the mines continue to exceed the mandated quartz PELs. MSHA's coal mine dust PEL for quartz is a reduced mining research establishment (MRE) equivalent respirable dust standard of (10 ÷ %quartz) mg/m^3 when there is more than 5% quartz present in the dust sample as determined by MSHA's P7 infrared method (Parobeck and Tomb, 2000; U.S. Code of Federal Regulations, 2004). MSHA's metal/nonmetal mine PEL for quartz is a reduced dust standard of (10 ÷ (%quartz + 2)) mg/m^3 for respirable dust containing at least 1% quartz as determined by NIOSH's X-ray method (Parobeck and Tomb, 2000; U.S. Code of Federal Regulations, 2004). The percentage of airborne dust samples taken between 1990 and 1999 that exceed the respirable quartz PEL for coal, metal and nonmetallic mining were 30.1%, 12.4% and 7.0%, respectively (NIOSH, 2003). These data indicate that there continues to be respirable dust overexposures in the mining industry.

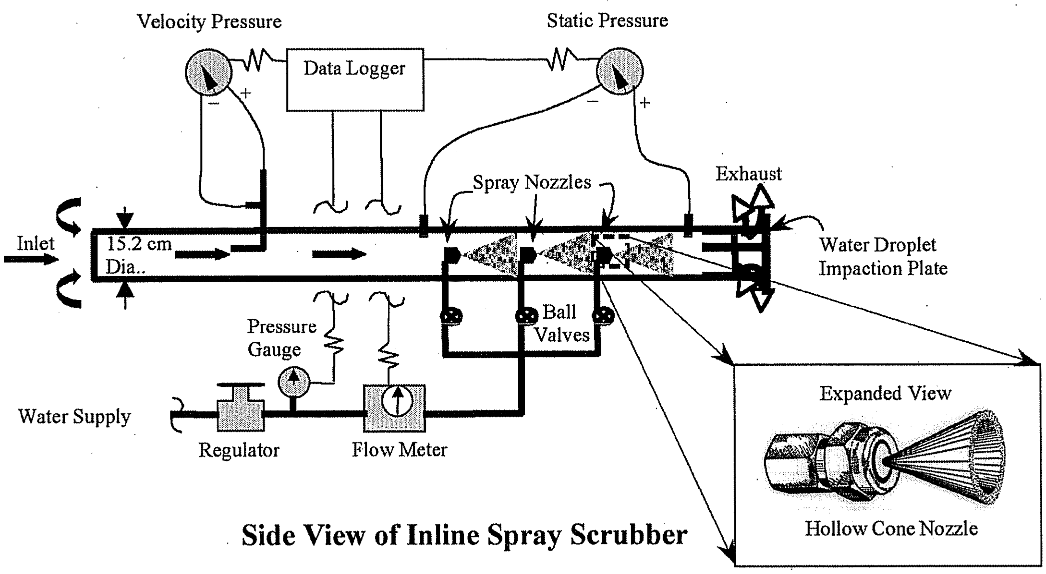

Figure 1 — Inline spray scrubber test apparatus for determining airflow inducement.

Directing spray nozzle flow through a small shrouded opening or duct induces airflow and significantly increases the capture efficiency of the spray droplets as compared to an unconfined area. This principle is the basis for the development of water-powered scrubbers by the Mining Research Development Establishment and U.S. Bureau of Mines (Jayaraman et al., 1981; Grigal et al., 1982; Kelly and Muldoon, 1987; Jayaraman et al., 1989). Many of the water-powered scrubbers developed were small-diameter tubes with high-pressure water sprays, greater than 3,447 kPa (500 psig) to achieve higher airflows through the tubes at higher dust capture efficiencies. Although these scrubbers proved to be very effective for underground coal mine dust control on continuous miners (spot scrubbers) and shearing machines (ventilated shearer drum), mine application was limited because of their higher water-pressure requirements, between 3,447 and 10,342 kPa (500 and 1,500 psig), for effective operation

While high water pressure is advantageous for confined spray dust capture (in scrubbers), it is detrimental to dust capture with unconfined water spray systems commonly used on mining machinery. Laboratory and underground research have shown that as the number of spray nozzles and the water pressure are increased for unconfined spray systems, the dust capture effectiveness per gallon of water is reduced (Schroeder et al., 1986). The improved dust capture from smaller higher velocity droplets at higher spray pressures is offset by the additional dilution from spray-induced airflow in the unconfined space (reduced residence time or droplet dust interaction). Thus, more dust knockdown for unconfined sprays will be achieved with higher water volume rather than pressure. It was also found during this research that operating unconfined water sprays at high pressures can also cause undesirable localized air turbulence, pushing contaminated dusty air to worker locations (continuous miner rollback) (Jayaraman et al., 1984).

To improve the airborne dust capture efficiency of water sprays in the mining industry, a water-powered scrubber with a lower operating pressure, i.e., <1,724 kPa (250 psig), was investigated and developed for more widespread user-friendly applications. Previous water-powered scrubbers were designed to achieve high airflow and dust-capture efficiencies by operating at water pressures greater than 1,724 kPa (250 psig) as noted above. To achieve higher scrubber airflow and dust-capture efficiencies at lower water pressures, i.e., <1,724 kPa (250 psig), a multiple inline spray series water-powered scrubber was investigated. This report describes the design parameter investigation of a low-pressure inline series spray scrubber, consisting of a 152-mm- (6-in.-) diameter tube with wide and narrow angle hollow cone spray nozzle arrangements.

Examination of scrubber operating parameters

Some early research on water-powered scrubber development has shown that the scrubber airflow capacity can be increased at lower spray operating pressures by placing nozzles in series along the enclosed tube, or in a co-planer pattern over a cross-sectional area of a tube (Grigal et al., 1982). This work also indicated that the pressure and flow characteristic of the scrubber was cumulative for multiple sprays in a series or co-planar arrangement at the same water pressures. The co-planar scrubbers were selected for further development because their arrangement could cover larger cross-sectional areas or ducts and had higher air induction rates per unit of spray water used. No further development or dust capture measurements were made on the inline or series spray scrubbers at the time of the research.

The current research study focused on several design variables of an inline series water spray scrubber. The scrubber design variables examined included spray discharge angle, number of inline sprays, inline spacing distance between sprays, water spray operating pressure, scrubber air pressure-airflow characteristics and dust capture efficiency. The preliminary scrubber design research classified the air pressure-quantity relationships generated by in-series sprays arranged inside a 3.05-m- (10-ft-) long, 152-mm- (6-in.-) diameter round pipe enclosure. Figure 1 shows the laboratory test setup (bench testing) to examine scrubber airflow inducement characteristics of various spray designs and inline spacing arrangements. This research focused on hollow cone spray nozzle designs because they produce the best water droplet atomization as compared to other single-fluid full-pattern spray types (flat fan, full cone, etc.). They also provide the best dust capture per gallon of water (U.S. Bureau of Mines, 1982; McCoy et al., 1985).

Two hollow cone nozzle designs were tested in the scrubber. One was a narrow discharge angle nozzle, Spraying Systems[1] UniJet No. ¼ TTD4-46 with a 33°-spray angle and an orifice diameter of 1.6 mm (0.063 in.). Its manufacturer's flow specifications are 3.0 L/min (0.78 gpm) of water flow at 551 kPa (80 psig) gauge pressure with a calculated discharge coefficient of 0.74 (actual flow divided by theoretical orifice diameter flow). The second nozzle tested was a wider discharge angle nozzle, Spraying Systems UnitJet No. ¼ TTD6-45 with an 81°-spray angle and an orifice diameter of 2.4 mm (0.094 in.). Its manufacturer's flow specifications are 3.1 L/min (0.83 gpm) at 551 kPa (80 psig) gauge pressure with a calculated discharge coefficient of 0.35.

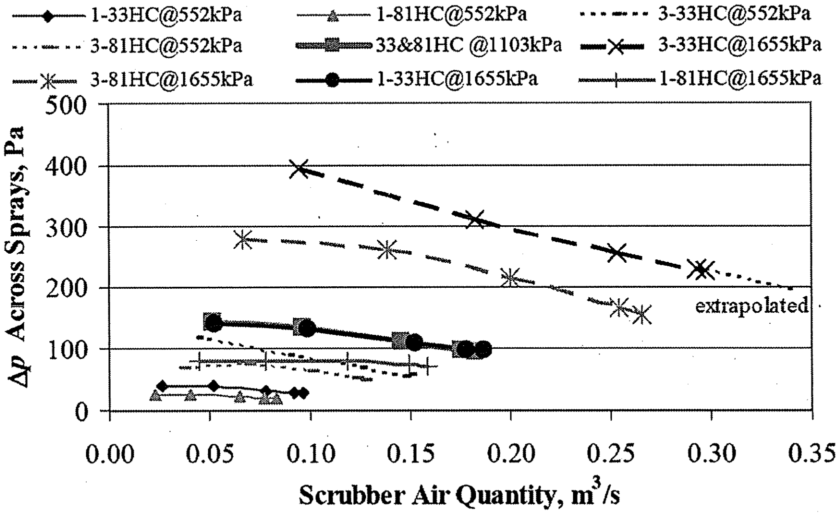

Figure 2 — Spray configuration static pressure and air quantity curves.

Up to three spray nozzles were spaced at either 152-mm (6-in.) or 305-mm (12-in.) distances apart, starting 610 mm (2 ft) away from the discharge end of the pipe. At the discharge end of the pipe, a perpendicular end plate was used to stop and remove the water droplets. The end plate was moved through various open positions, i.e., 12.7, 25.4, 50.8, 102 and 203 mm (0.5, 1, 2, 4 and 8 in.), to measure the air pressure-flow characteristic generated by the spray arrangement at various scrubber airflow resistances. Initially, each spray arrangement was measured at two water pressures of 551 and 1,103 kPa (80 and 160 psig). The operating spray arrangements tested were a single spray closest and furthest away from the scrubber discharge, the two sequential sprays closest and furthest away from the scrubber discharge and all three sprays.

Using a pitot tube, scrubber airflow or velocity measurements were made eight diameters or 1.22 m (4 ft) from the scrubber entrance. Static pressure differential pressure measurements created by the sprays nozzle arrangements were made between the midpoint of the pipe, i.e., 1.52 m (5 ft) from the entrance or discharge, and 305 mm (1 ft) from the discharge end of the pipe. Water flow and pressure were also monitored downstream of a pressure regulator in the supply line to the spray nozzles. These scrubber parameters were continuously recorded on a four-channel data logger for five minutes and averaged during each test condition. These test data were compiled into 40 air pressure-flow characteristic curves. The 305-mm (1-ft) distance between sprays was found to yield higher air pressure-flow characteristic curves for the 33° hollow cone sprays than the 152-mm (6-in.) spacing, whereas there was no noticeable spacing effect for the 81° hollow cone sprays. Thus, all the inline spray testing for dust capture was limited to the 305-mm (1-ft) spacing for simplification. Several of the spray configurations, i.e., one spray and three sprays at 305 mm (12 in.) apart, were also tested at 1,654 kPa (240 psig) to boost scrubber airflow even more. Scrubber airflow quantities greater than 0.24 m^3/s (500 cu ft per min) were achieved with three spray nozzles of either type operating at 1,654 kPa (240 psig).

Figure 2 shows the air pressure-flow characteristic curves for the scrubber configurations to be tested in the dust chamber. These were selected for the dust chamber testing because they represent the scrubber configuration design range for examining dust capture efficiency effects. These curves show that scrubber airflow output is increased by the number of sprays nozzles and their operating pressures. They also show that the narrower angle hollow cone sprays consistently provide a higher static air pressure-quantity curve than the wider-angle hollow cone sprays tested at similar scrubber configurations.

Spray nozzle design effects on water droplet size distributions and droplet velocities can be observed from separate Phase Doppler Particle Analyzer (PDPA) measurements made on each of these two hollow cone nozzles operating at 551 and 1,103 kPa (80 and 160 psig). Although these were individual unconfined spray nozzle droplet measurements, their confined scrubber tube droplet characteristic changes with respect to operating pressure are expected to be relatively similar. Water droplet size characteristics are expected to be relatively larger for both nozzles inside the scrubber tube due to droplet coalescence in a confined air stream and multiple inline spray interactions. The PDPA measurement method description can be found in Gemci et al., 2003.

Figures 3 and 4 show the Sauter mean diameter (SMD or D_{32}) and mean droplet velocity measurements for the 33° hollow cone spray and for the 81° hollow cone spray, respectively, 0.3 m (1 ft) away and on a radial pattern from the centerline of the nozzle orifice. The actual measurements were made at the points connected by the solid lines, which were asymmetrically projected to the other side of the spray centerline. The darker lines are the SMD curves and the lighter lines are the mean droplet velocity curves. The thinner lines are the droplet characteristics for the 552 kPa (80 psig) water pressures and the thicker lines are the droplet characteristics for the 1,103 kPa (160 psig). Arrows indicate which y-axis the curve belongs to.

The Sauter mean diameter (SMD or D_{32}) is the summation of the total volume of sampled spherical droplet diameters divided by the summation of their total surface area. This represents the mean diameter ratio of droplet volume to droplet surface area generated by the nozzle and is the most commonly used mean droplet diameter representation in mass transfer reaction applications.

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[1] Mention of any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

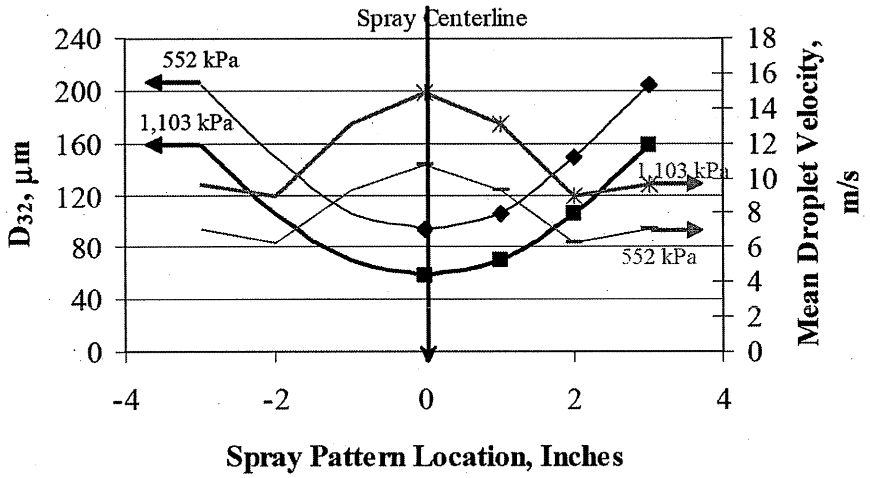

Figure 3 — Spray droplet characteristics for the 33° hollow-cone spray nozzle.

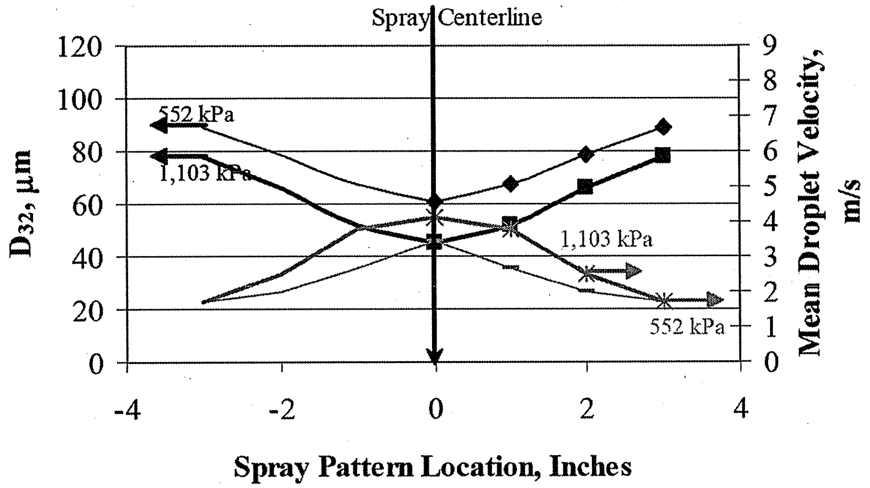

Figure 4 — Spray droplet characteristics for the 81° hollow-cone spray nozzle.

Both of these droplet size and velocity figures notably show that the narrower hollow cone spray angle nozzle had larger droplet SMDs and higher droplet velocities throughout the spray pattern as compared to the wider-angle hollow cone nozzle. Also, these spray droplet size and velocity figures show that by increasing nozzle operating pressures, SMD decreased and average droplet velocity increased throughout the spray pattern range. Thus, larger water droplet SMDs and higher droplet velocities appear to be the driving energy source for higher water-powered scrubber airflow inducement for the 33° hollow cone nozzle as compared to the 81° nozzle.

Laboratory dust capture experiments

Dust chamber experiments were conducted on various scrubber configurations to examine the key factors in in-line series spray dust capture. The inline series dust collection efficiency testing was conducted in a 2.44-m- (8-ft-) high, 2.44-m- (8-ft-) wide, 2.44-m- (8-ft-) deep closed system dust chamber. An air inductor into the closed system dust chamber injected dust until it reached a desired dust concentration ceiling. A 1.1-m^3/s (2,300-cu ft per min) mixing fan in the chamber was used to disperse the injected dust throughout the chamber before the test. Airborne dust capture efficiency of the scrubber was determined by the removal rate of a known amount of dust in a known volume of the chamber over the application time period. The dust removal rate or chamber dust concentration decay rate was determined by (Ruggieri et al.,1983; McCoy et al., 1985)

$$\frac{dC}{C} = \frac{-\eta Q}{V}\, dt \qquad (1)$$

When solved this reduces to

$$\eta Q = \frac{-V}{t}\ln\left(\frac{C}{C_o}\right) \qquad (2)$$

where

C is the final dust concentration (mg/m^3),
C_o is the initial dust concentration (mg/m^3),
Q is the air quantity scrubbed (m^3/s),
V is the fixed volume of closed system (m^3),
t is the time (seconds),
ηQ is the dust removal or cleaned airflow rate (m^3/s) and
η is the dust capture efficiency (%).

The dust removal rate or dust capture efficiency measured during the experiment is the cumulative dust capture of all the mechanisms taking place in the dust chamber. This includes the scrubber as well as other background removal mechanisms of the chamber (settling, impact-adhesion, etc.). Generally, all these background removal mechanisms become a notably smaller portion of the dust capture measurement when water spray or scrubber testing is conducted at higher dust concentrations in the enclosed dust chamber (Ruggieri et al.,1983; McCoy et al., 1985). Thus, most of the dust removal rate or dust capture efficiency measurement can be attributed to the scrubber.

This closed-system dust-chamber testing procedure was used successfully in the past to conduct comparative dust capture rates of various types of unconfined sprays (air-atomizer, hollow cone, full cone, flat fan) and a water-powered scrubber operating in the center of the chamber (Ruggieri et al.,1983; McCoy et al., 1985). It was also used for comparative dust capture testing of a hollow cone spray on various bituminous coal types (Organiscak and Leon, 1994). An advantage of a closed dust chamber system is that a comparable dust removal or cleaned airflow rate (ηQ) can be measured for open sprays, enclosed scrubber sprays and partially enclosed sprays. Another advantage is that the same aerosol sampling equipment utilized in field sampling can be located at a position away form the spray pattern or highest area of airflow turbulence, whereas testing in an open wind tunnel system requires changing the dust sampling equipment to meet the velocity conditions in the wind tunnel (iso-kenetic sampling). One disadvantage or drawback of the closed system approach is that some level of dust gradients exists in the chamber as compared to the mathematical model assumption of uniform dust concentrations throughout the chamber (Organiscak and Leon, 1994). However, past experience has shown that this drawback can

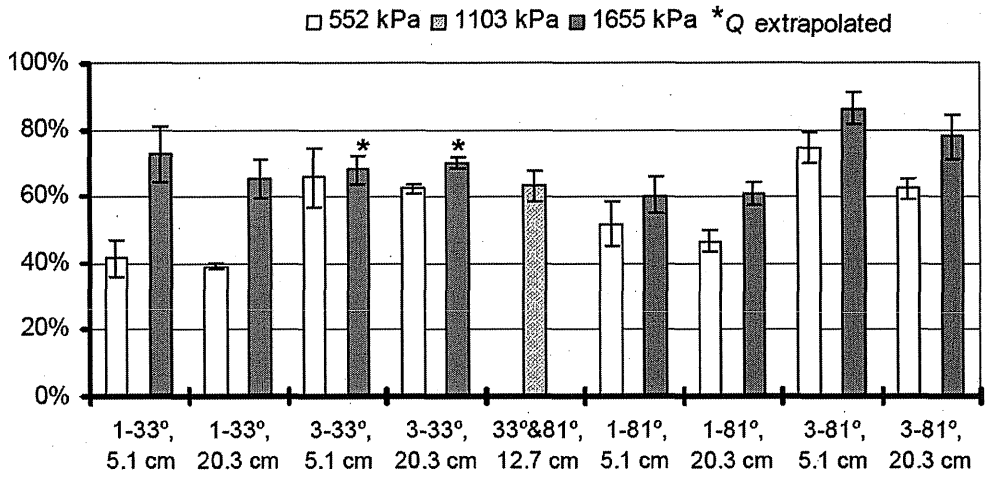

Figure 5 — Scrubber dust capture efficiencies.

be reduced by sampling in a more stable area (usually in the center) of the dust chamber.

Dust-capture performance measured during this scrubber testing was conducted by personal gravimetric dust samplers for a given time period before and after operating the water-powered scrubber, with instantaneous real-time dust sampling conducted during the complete test. Particular to this experiment, Keystone Mineral Black 325 BA of particle size less than 44 μm (Keystone Filler and Manufacturing Co., Muncy, Pennsylvania) was injected into the dust chamber to achieve a little more than 100 mg/m^3 of respirable dust concentration, as measured with an instantaneous real-time dust monitor (RAM-1, MIE, Inc., Bedford, Massachusetts). The RAM-1 was operated at 2.0 L/min with a Dorr-Oliver 10-mm nylon cyclone to measure the respirable size fraction of dust. When the instantaneous respirable dust concentration naturally decayed to 100 mg/m^3, two personal MSA coal mine dust samplers were run for a three-minute interval to determine the initial average respirable gravimetric dust concentration for calibrating the RAM-1 dust concentration at the beginning of the scrubber decay (C_o). The MSA coal mine dust samplers were made up of an Elf personal sampling pump drawing 2.0 L/min of air through a Dorr-Oliver 10-mm nylon cyclone, which collected the respirable fraction of airborne dust on an MSA coal mine filter cassette. Following the completion of the initial three-minute sampling period, the scrubber was operated for various time periods to reduce RAM-1 dust concentrations to around 30 mg/m^3. After the scrubber operation was stopped, another two personal MSA coal mine dust samplers were run for a 10-min period to determine the final average respirable gravimetric dust concentration for calibrating the RAM-1 dust concentration (C) at the end of the scrubber decay.

The scrubber dust capture efficiency performance configurations tested in the chamber were conducted in the operating ranges of the scrubber air pressure and quantity characteristic curves developed previously and shown in Fig. 2. The experimental factors included hollow cone discharge angle (33° vs. 81°), spray number (one vs. three), spray operating pressure (552 vs. 1,655 kPa or 80 vs. 240 psig), and scrubber demister resistance (50.8 vs. 203 mm, or two vs. eight in exit opening). A midpoint scrubber configuration tested within these ranges was one 33° and 81° (spaced 610 mm or 2 ft apart), operating at 1,103 kPa (160 psig) and a 127 mm (5 in.) demister exit opening. Seventeen scrubber configuration experiments were randomly conducted for at least three repetitions for each configuration.

The initial scrubber was modified by cutting off the first 1.22 m (4 ft) of scrubber inlet used in developing the air pressure and quantity curves (see Fig. 1) to shorten it to 1.83 m (6 ft) in length so it would horizontally fit into the dust chamber. During these experiments the water flow, water pressure and scrubber static pressure were continuously recorded. The scrubber airflow (Q) was indirectly determined by using the average scrubber static pressure upstream and downstream of the spray region to determine the scrubber quantity from the previously developed performance curves in Fig. 2. The static differential pressure for three inline series 33° HC sprays operating at 1,655 kPa (240 psig) appeared to be a little lower for the shorter scrubber (1.83 m or 6 ft) than the previously measured curve for the longer scrubber (3.05 m or 10 ft), so the air quantity was determined by extrapolating the existing curve to the lower pressures. Using the scrubber air quantity (Q), chamber volume (V), scrubbing time (t), initial dust concentration (C_o) and final dust concentration (C), the scrubber dust capture efficiency (η) could be determined from the above decay model.

A previous scrubber efficiency study determined that the enclosed chamber test method resulted in a slight overprediction of scrubber efficiency (3% higher) as compared to the intake and exhaust gravimetric testing of the scrubber (McCoy et al., 1985). The test chamber used in the present experiments showed about a 1% background decay efficiency after the chamber was wetted with a water spray, dust injected, and mixed with the 1.1-m^3/s (2,300-cu ft per min) mixing fan (no spray operating) over the same time periods that the scrubber was tested. Thus, background dust chamber decay efficiencies were considered negligible in the scrubber efficiency determinations.

Dust capture results

The inline series water-powered scrubber test results are shown in Fig. 5 and indicate that both water pressure and the number of inline sprays noticeably affected the water-powered scrubber performance. Figure 5 shows the scrubber efficiency averages and standard deviations for the configurations tested. A single 33° HC spray showed somewhat lower average dust capture efficiencies (39% to 42%) when operating at 552 kPa

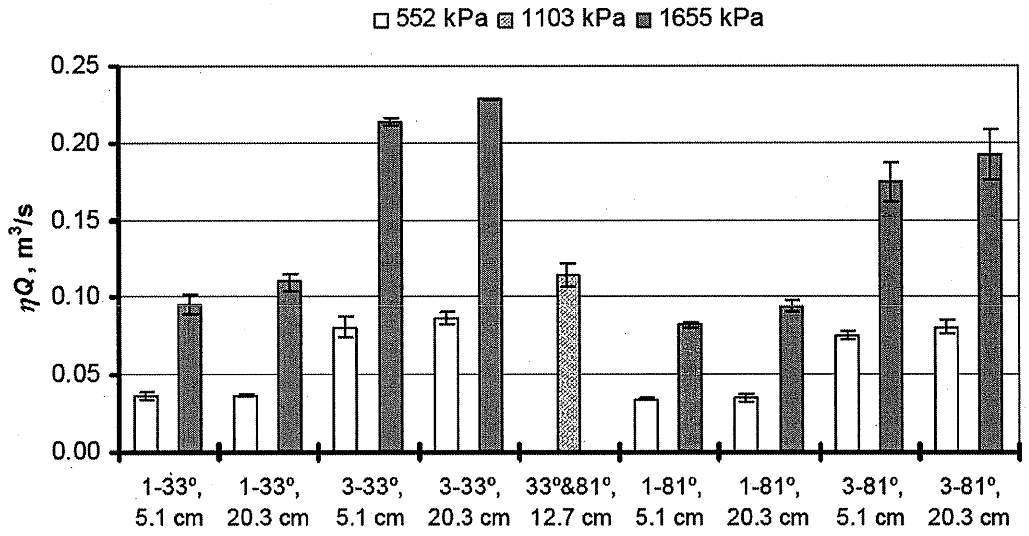

Figure 6 — Scrubber dust removal or cleaned airflow rates.

(80 psig) than the 81° HC spray (47% to 52%), but its average efficiencies more notably increased and were slightly higher (65% to 73%) than the 81° HC spray (60% to 61%) when operated at 1,655 kPa (240 psig). To gain some insight into this spray nozzle performance difference, previously measured water droplet formation characteristics for each nozzle can be examined (see Figs. 3 and 4). These figures show that the 33° HC spray had a notably larger increase in average droplet velocity, and a notably larger decrease in SMD, throughout the spray pattern in comparison to the 81° HC spray at increased operating water pressures from 552 to 1,103 kPa (80 to 160 psig). This indicates that both higher droplet velocities and smaller water droplet sizes are components for increased dust capture (Calvert, 1977) and airflow through the scrubber at higher water spray pressures (see Fig. 2). Water quantity is also another dust capture efficiency component related to increasing operating pressure, since the quantity passing through a nozzle or orifice is directly proportional to the square root of the higher operating pressure divided by the square root of the lower operating pressure.

The independent scrubber water quantity effect of adding additional spray nozzles, irrespective of the operating pressures, can also be seen from Fig. 5. Increasing the number of the same sprays in the scrubber at the same spray operating pressures also showed an increase in the dust capture efficiency. The average dust capture efficiency for the 33° HC spray operating at 552 kPa (80 psig) rose from about 40% to more than 60% when two more sprays were added at that same pressure. The average dust capture efficiency for the 81° HC spray operating at 552 kPa (80 psig) rose from about 50% to more than 60% when two more sprays were added at that same pressure. Scrubber dust capture efficiencies increased to between 68% and 86% when using three of either type of water spray nozzle operated at 1,655 kPa (240 psig). The two-spray 33° HC and 81° HC combination inline scrubber operating at 1,103 kPa (160 psig) water pressure also showed an average dust capture efficiency of 63%, which is a good dust capture efficiency compromise between the single- and three-spray configurations operating at 1,655 kPa (240 psig).

Another way of examining the inline spray scrubber performance is to examine dust removal or air cleaning rate ηQ with respect to scrubber configurations (McCoy et al., 1985). This performance measure is determined irrespective of scrubber airflow quantity by using above dust chamber decay equation. Figure 6 shows the averages and standard deviations of this scrubber performance measure (ηQ) for the different spray configurations tested. This figure shows that both water pressure and the number of water sprays (water quantity irrespective of pressure) clearly increases ηQ. The 33° HC spray also shows a noticeable increase in ηQ over the 81° HC spray at the higher water spray pressures (1,655 kPa or 240 psig). This is due to the higher scrubber air quantity throughput of the 33° HC spray over the 81° HC spray at higher water spray pressures and elevated dust capture efficiencies (see Figs. 2 and 5).

The water quantity impact of the various scrubber spray configurations on ηQ can be more clearly seen in Fig. 7. This graph shows the scrubber water quantities measured during dust capture testing, with each cluster of points representing distinct spray configurations at their multiple demister end plate settings. As can be seen in this figure, water quantity increases with both pressure and the number of sprays added. The biggest increases to ηQ with respect to water quantity were from changes in pressure. Using three sprays at lower water pressures and higher water quantities as compared to a single spray at higher water pressures and lower water quantities yielded about the same ηQ. Thus, similar ηQs can be achieved by adding more sprays at lower pressures or by using one spray at higher pressures.

To examine the dust capture efficiency of all these spray configurations on more comprehensive terms, the power input of the spray(s) was normalized by the scrubber airflow for each individual test and is shown in Fig. 8. Because water spray power is a product of nozzle operating pressure and water quantity, they are jointly factored into spray power. This figure indicates that a general direct logarithmic relationship exists between scrubber spray power input per airflow induced and the capture efficiency during these experiments. It also shows that spray power per unit of airflow can be achieved by increasing water pressure and/or quantity. The spreads in the individual points are likely due to the various water droplet characteristics present during the different spray configurations

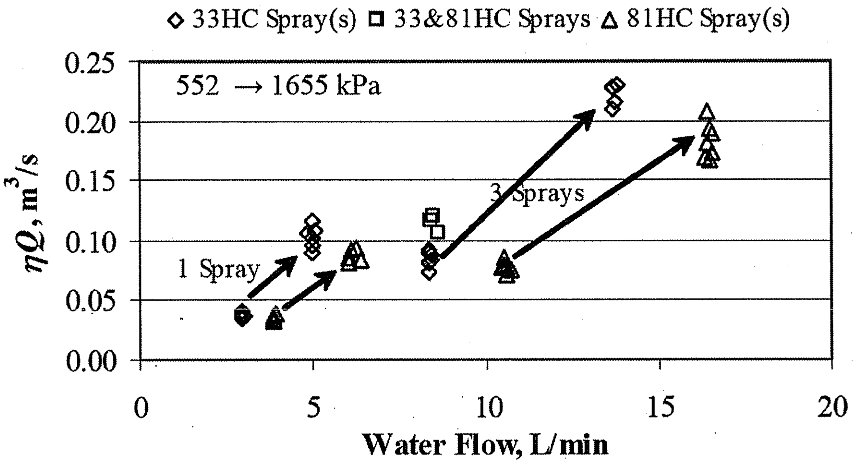

Figure 7 — Water flow rate relationship to scrubber cleaned airflow rate.

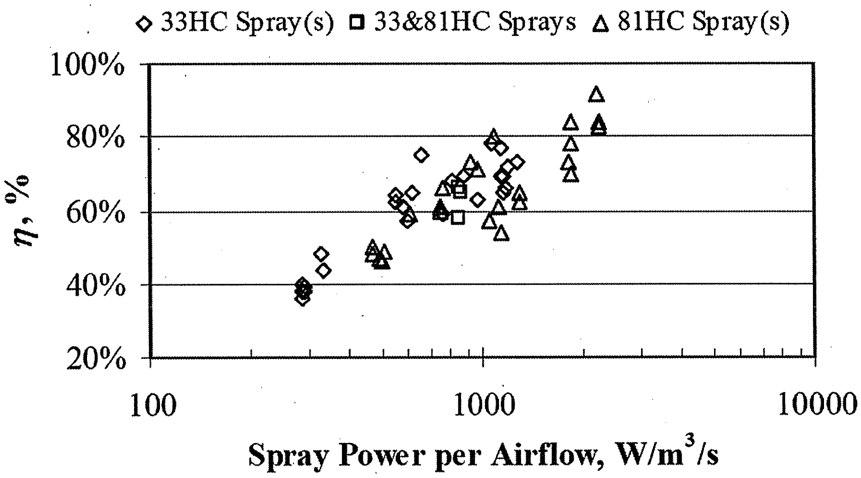

Figure 8 — Spray power and efficiency relationship.

tested and experimental error of the individual tests. Again, Figs. 3 and 4 illustrate some of the noticeable differences in spray droplet characteristics for the 33° HC and 81° HC nozzle designs, with pressure increases from 552 to 1,655 kPa (80 to 240 psig). However, quantifiable spray droplet effects on dust capture efficiency cannot be easily assessed from the limitations of these experiments.

Conclusions

Inline series water-powered scrubber laboratory tests show that spray operating pressure and number of inline sprays noticeably affected the water-powered scrubber airflow and dust-capture efficiency. The narrower 33° HC spray nozzle angle consistently developed higher static differential pressures and scrubber air quantities than the 81° HC spray nozzle for all the operating pressures and number of sprays used. Independent phase doppler measurements of spray droplets generated from unenclosed hollow cone nozzles showed that the narrower 33° angle hollow cone spray pattern had a larger droplet size distribution with faster velocity droplets than the wider 81° angle hollow cone nozzle, which likely explains its better scrubber airflow inducement. Dust capture efficiencies for either spray operating at 552 kPa (80 psig) were increased on average from 39% to 52% to between 62% and 86% by increasing water pressure to 1,655 kPa (240 psig) and/or adding two more sprays in series operating at 552 to 1,655 kPa (80 to 240 psig) water pressures.

Increasing the spray pressure and/or the number of sprays also increased the air-cleaning rate of the scrubber (ηQ). Similar air cleaning rates (ηQ) were observed for one spray operating at 1,655 kPa (240 psig) as compared to three sprays operating at 552 kPa (80 psig). Increasing the water pressure appeared to make greater increases in the air cleaning rates (ηQ) with respect to water flow rate rather than adding sprays at the same water pressure. This seemed to be a result of higher scrubber airflow inducement at higher water pressures and scrubber efficiencies.

Examining scrubber performance on more comprehensive terms — of spray power input per unit of airflow induced — illustrated a direct logarithmic relationship with scrubber dust capture efficiency (η). Higher scrubber dust capture efficiencies were achieved by increasing spray power input through either increased water pressure and/or number of sprays. Thus, inline spray scrubber efficiency trade-offs can be made by altering spray power components of water pressure and/or quantity (number of sprays). Results show that on average up to 0.23 and 0.32 m^3/s (484 and 679 cu ft per min) of airflow at 0.81 and 0.69 dust capture efficiencies can be achieved with three

81° and 33° hollow cone inline series sprays, respectively, operating at 1,655 kPa (240 psig).

The in-line series spray scrubber operating at lower water pressures, i.e., ≤1,724 kPa (≤250 psig), than previously developed water powered scrubbers should be more user-friendly for more widespread mining application. They are portable scrubbers that can be located in high dust concentration areas near generation sources while capable of being operating by many existing water supply systems. Future mining applications that should be targeted with these scrubbers are continuous mining machines, shearers, crushers, and stone cutting machines. The scrubber(s) can be integrated into the existing spray systems to improve its overall dust capture effectiveness.

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