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Empirical engineering models for airborne respirable dust capture from water sprays and wet scrubbers

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Abstract

Airborne respirable coal dust capture by water sprays or wet scrubbers has been studied and developed over many decades as an engineering control to reduce dust exposure in coal mines and combat coal worker pneumoconiosis. Empirical relationships and deterministic models for particular dust capture experiments have previously been devised to show the key parameters involved in airborne coal dust capture. Many of the results from these models show that the significant parameters related to airborne dust capture are water spray pressure, water quantity, water droplet size, relative water droplet-to-dust particle velocity, and total operating air pressure of the scrubber. However, many airborne dust capture efficiency relationships and models developed for particular experiments cannot be readily applied to forecast the dust collection efficiency of different spray and scrubber design configurations, which rely on several key dimensional engineering measures. This study examines engineering measures from previous water spray and wet scrubber experiments conducted by the U.S. National Institute for Occupational Safety and Health (NIOSH) and the U.S. Bureau of Mines (USBM) to develop empirical models for wet collection of airborne dusts. A dimensionless empirical model developed for predicting airborne dust capture efficiency of water sprays and wet scrubbers is presented.

Introduction

Water sprays have been one of the earliest mainstay engineering controls used to suppress respirable dust in underground coal mines. Some of the earliest reports of water spray usage on continuous mining machines indicated respirable coal mine dust reductions of 20 to 60 percent (Kobrick, 1970). Not long after the enactment of the 1969 Coal Mine Health and Safety Act, the U.S. Bureau of Mines (USBM) and others conducted extensive research into water spray and wet scrubber systems to control respirable dust in coal mines. The primary aspects of water spray dust control included prewetting for dust prevention, localized ventilation redirection and airborne dust capture, which are summarized in handbooks or best-practices guides (Kost, Yingling and Mondics, 1981; Kissell, 2003; Colinet et al., 2010). Initially, underground studies were conducted to identify the primary sources of dust during the mining processes and effective dust controls (Courtney, Jayaraman and Behum, 1978; Jankowski and Organiscak, 1983). Laboratory research systematically studied ventilation and airborne dust capture effects of water sprays and scrubbers to improve their application in underground coal mines (Tomb, Emmerling and Kellner, 1972; Divers and

Janosik, 1978, 1980; Grigal et al., 1982; Ruggieri et al., 1983; Jayaraman, Jankowski and Kissell, 1985; Volkwein, Ruggieri et al., 1985; Jayaraman, Schroeder and Kissell, 1986; Divers, Jankowski and Kelly, 1987; Jones and James, 1987).

In the laboratory, water sprays were found to be more efficient on airborne respirable dust capture at higher water spray pressures (Tomb, Emmerling and Kellner, 1972; Jayaraman, 1982; Ruggieri et al., 1983; McCoy et al., 1985). Water sprays operating at higher pressures — above 690 kPa (100 psig) — and placed inside ducts showed additional increases in airborne respirable dust capture, leading to specific water-powered scrubber applications in mining (Grigal et al., 1982; Jones and James, 1987; Divers, Jankowski and Kelly, 1987; Jayaraman, Jankowski and Babbitt, 1989). Although higher water spray pressures improve airborne respirable dust capture, they can cause dust rollback on continuous mining machines (Jayaraman, 1985). Locating water sprays on the underside of the cutter boom increased their airborne dust capture compared to locating them on the topside of the cutter boon, particularly when adding more, from three to 11, water sprays to increase water flow rates (Jayaraman, Schroeder and Kissell, 1986). The airflow interaction from the larger number of sprays at higher water pressures diminishes the airborne capture efficiency per volume of water used (Jayaraman, Schroeder and Kissell, 1986). Additional laboratory testing of 12 topside and six underside boom sprays similarly indicated diminishing airborne respirable dust knockdown from hollow-cone sprays with pressure increases to about 965 kPa (140 psig) water spray pressure and 95 L/min (25 gpm) of water flow (Colinet, McClelland and Jankowski, 1991).

Fan-powered scrubbers were likewise studied in the laboratory to examine their airborne effects on dust capture efficiencies for applications in coal mines. The types of scrubbers studied included wetted-fan, cyclone, venturi, flooded-bed and brush scrubbers (Divers and Janosik, 1978, 1980; Grigal et al., 1982). Many of these scrubbers were found to have airborne respirable dust capture efficiencies greater than 80 percent and were primarily related to water spray flow rate and the scrubbers' total operating air pressure (Divers and Janosik, 1978, 1980; Grigal et al., 1982). Flooded-bed scrubbers achieved airborne dust capture efficiencies greater than 90 percent. Flooded-bed scrubbers were initially used with blowing face ventilation systems in underground gassy coal seams to help remove dust being blown over workers generated at the mine face, while providing satisfactory face methane removal for curtain setback distances up to 15.2 m (50 ft) (Volkwein, Halfinger et al., 1985; Jayaraman, Volkwein and Kissell, 1990). With the development of remote control technology for continuous mining machines, flooded-bed scrubbers were also adopted on exhaust face ventilation systems for use in extended-cut mining applications beyond 6.1 m (20 ft) of entry advance. Flooded-bed scrubber applications on continuous mining machines with a 12.2-m (40-ft) exhaust curtain setback from the face showed significant reductions in airborne dust compared to just using machine-mounted water sprays with a 6.1-m (20-ft) exhaust curtain setback from the face (Colinet and Jankowski, 1998; Colinet, Reed and Potts, 2013; Organiscak and Beck, 2014). Experimental laboratory research also indicated that sulfur hexafluoride gas concentration reductions could be achieved at the face by using a scrubber with a 12.2-m (40-ft) exhaust curtain setback compared to a 6.1-m (20-ft) exhaust curtain setback without a scrubber (Organiscak and Beck, 2014). NIOSH research further shows that continuous mining machine dust reductions are directly related to scrubber airflow quantities used at the mining face (Organiscak and Beck, 2010; Potts, Reed and Colinet, 2011).

The fundamental variables involved in water spray dust capture have been mathematically modeled to study the most influential variables. Typical open space and enclosed duct spray models were based on inertial-interceptional dust collection mechanisms using intercept droplet length and interparticle area (Cheng, 1973; Jones and James, 1987; Charinpanitkul and Tanthapanichakoon, 2011). These models were found to agree reasonably well with experimental spray dust capture results, but numerous variables are needed to accurately model the spray's airborne dust capture. Other researchers more simply related several empirical spray operating parameters to airborne dust capture. Common spray operating parameters studied include spray operating pressure, water flow rate, water flow to airflow ratio and spray power to airflow ratio (Jayaraman, 1982; Jones and James, 1987; Organiscak and Pollock, 2007; Pollock and Organiscak, 2007).

Many of the spray operating parameters are related to the fundamental inertial-interceptional dust collection mechanisms. Spray nozzle parameters such as orifice diameter are directly related to water quantity at constant pressure, while discharge angle is indirectly related to droplet size and velocity at constant pressure (Streeter and Wylie, 1979; Pollock and Organiscak, 2007; Klima et al., 2017). Water spray operating pressure is indirectly related to water droplet size and directly related to water droplet velocity for a particular spray nozzle (Cheng. 1973; Jones and James, 1987; Pollock and Organiscak, 2007). Although many empirical relationships with airborne dust capture have been identified, they are usually limited to the particular experimental conditions and cannot be easily extrapolated to other dimensional testing conditions. The purpose of the present work is to examine previous experimental variables measured by USBM and NIOSH in laboratory dust capture experiments and formulate an empirical model that best describes the dust capture efficiency for the various types or designs of water spray and wet scrubber systems.

Methodology

The following approach was taken in reviewing the literature and formulating the empirical model:

- Reviewed water spray and wet scrubber literature to identify fundamental variables for water droplet airborne dust capture.
- Re-examined data from the most recent NIOSH laboratory water spray droplet characterization and dust capture studies.
- Empirically analyzed the key variables from the recent studies with respect to airborne respirable dust capture.
- Identified additional relevant data available from previous USBM water spray and wet scrubber testing publications.
- Conducted a dimensional analysis of the variables involved in respirable dust capture, including several operating variables universally related to fan scrubbers.

- Formulated an empirical model from dimensionless parameters to quantify various water spray and wet scrubber configurations related to airborne dust capture efficiency.

The foremost literature reviewed for this topic is contained at the end of this paper. The research studies from which data were re-examined for the modeling analyses are listed in Table 1.

Water spray and water-powered scrubber analysis.

Multivariable regression analysis was initially conducted on the data most recently collected from the water-powered scrubber and unconfined spray research. Droplet size, relative water droplet-to-dust particle velocity, air quantity, and water quantity are the key fundamental variables for wet scrubbing mechanisms for inertial-interceptional dust collection (Cheng, 1973; Jones and James, 1987; Gemci, Chigier and Organiscak, 2003; Charinpanitkul and Tanthapanichakoon, 2011). Water droplet size distributions decreased with corresponding droplet velocity increases at higher spray operating pressures (Gemci, Chigier and Organiscak, 2003; Pollock and Organiscak, 2007). This corresponds to higher airflow induction quantities and airborne dust capture efficiencies for the various water sprays and water-powered scrubber configurations tested (Organiscak and Pollock, 2007; Pollock and Organiscak, 2007). The effective mean velocity differences between water spray droplets and induced airflows of dust-laden air can be determined by rearranging the momentum transfer relationship:

$$N_m = \frac{p_a A_s}{\dot{m}_w (V_i - V_a)} \quad (1)$$

into:

$$N_m (V_i - V_a) = \frac{p_a A_s}{\dot{m}_w} \quad (2)$$

and, assuming $N_m = 1$ and V_i becomes V_w, reformulating it into (Grigal et al., 1982):

$$(V_w - V_a) = \frac{p_a A_s}{\dot{m}_w} \quad (3)$$

where N_m is the fractional momentum transfer efficiency; p_a is the total pressure rise from the spray induction of airflow in force per unit area; A_s is the cross-sectional area of the mixing section in length squared; $\dot{m}_w$ is the mass flow rate of water in mass units per second; V_i is the ideal nozzle water velocity, equal to $\sqrt{(2p_w/\rho_w)}$, in length per second; p_w is the water pressure at nozzle in force per unit area; ρ_w is the water density in mass per volume;

V_w is the mean water droplet velocity, equal to $V_i \times C_v$, in length per second, where C_v is defined below; and V_a is the mean air velocity of air induction in length per second.

The mean water droplet velocity is less than the ideal droplet velocity because as the spray nozzle discharge angle increases, velocity losses are incurred. These losses are described by a discharge coefficient, C_v, which is a ratio of the actual (or mean) water exit velocity of the spray nozzle to the ideal water velocity of a steady stream for a similarly sized orifice (Streeter and Wylie, 1979). If we assume that all the momentum transfer from the mean droplet velocity is transferred to the airflow movement, such that $N_m = 1$, we can determine the relative difference, $V_w - V_a$, between the spray water droplets and the airflow movement. The relative water droplet to airflow velocity was one of the key variables used in the water-powered scrubber and unconfined spray regression analysis with respirable dust capture efficiency. The other key laboratory variables measured and used in this analysis were airflow quantity and water flow quantity. They were reconfigured into a second regression variable of the air mass flow rate divided by the water mass flow rate, using mass-volume densities at standard air temperature and pressure.

Dimensional analysis — Buckingham Pi theorem.

In order to accommodate fan-powered wet scrubbers with water-powered scrubbers and unconfined sprays into an inclusive airborne dust collection model, a dimensional analysis was performed on the key influential dimensional engineering measures presented within the multiple studies shown in Table 1. The dimensional analysis approach was taken because it allows generalization of experimental data to describe useful relationships in its entirety and is not limited to the particular experiment that was performed (Streeter and Wylie, 1979). Dimensionless analysis is based on the Buckingham Pi theorem that a physical problem having n variables and m dimensions can be arranged into $n - m$ independent dimensionless parameters ($\Pi_1, \Pi_2, \ldots, \Pi_{n-m}$) (Buckingham, 1915; Streeter and Wylie, 1979). The premise of this theorem is that some functional relationship exists for the quantities known to be essential to the solution. The method of determining the dimensionless parameters is to select repeating variables that collectively include all m dimensions of the physical problem, combine these repeating variables with each of the other physical quantities in the problem, and solve for the exponents of each parameter that make it dimensionless (Streeter and Wylie, 1979).

Figure 1 shows the two-dimensional drawing of a water-powered or fan-powered wet scrubber problem illustrated with the key engineering variables used in the Buckingham Pi analysis. The variable function relationship for this dimensional analysis of Fig. 1 is shown in:

$$F\left(A_S, L_S, p_w, p_a, \Delta V, \dot{m}_w, \dot{m}_a, \eta_d\right) = 0 \quad (4)$$

with Table 2 showing the relevant variables and their corresponding dimensions. The repeating variables chosen for this analysis were A_s, p_a and $\dot{m}_w$ with dimensional depictions of M, L, and T for mass, length, and time, respectively. The dimensionless groupings or parameters in this analysis for the repeating and nonrepeating variables are illustrated in the following:

$$f\left(\Pi_1, \Pi_2, \Pi_3, \Pi_4, \Pi_5\right) = 0 \qquad (5)$$

with

$$\Pi_1 = \left(A_s^x p_a^y \dot{m}_w^z\right) L_s, \Pi_2 = \left(A_s^x p_a^y \dot{m}_w^z\right) p_w, \Pi_3 = \left(A_s^x p_a^y \dot{m}_w^z\right) \Delta V, \Pi_4 = \left(A_s^x p_a^y \dot{m}_w^z\right) \dot{m}_a, \Pi_5 = \left(A_s^x p_a^y \dot{m}_w^z\right) \eta_d$$

The three exponents that need to be solved for the first dimensionless parameter are shown in:

$$\Pi_1 = \left(A_s^x\, p_a^y\, \dot{m}_w^z\right) L_S = \left(L^2\right)^x \left(M\, L^{-1}\, T^{-2}\right)^y \left(M\, T^{-1}\right)^Z L = M^0 L^0 T^0 \qquad (6)$$

The solution of Eq. (6) for the exponents of the first dimensionless parameter, where:

$$y + z = 0; \text{ for the M dimension} \qquad (7)$$

$$2x - y + 1 = 0; \text{ for the L dimension} \qquad (8)$$

$$-2y - z = 0; \text{ for the T dimension} \qquad (9)$$

$$x = -1/2, y = 0, z = 0 \qquad (10)$$

is

$$\Pi_1 = \frac{L_S}{\sqrt{A_S}} \qquad (11)$$

Continuing on with the solution of the other dimensionless groupings, we end up with:

$$f\left(\frac{L_S}{\sqrt{A_S}}, \frac{p_w}{p_a}, \frac{\dot{m}_W \Delta \mathrm{V}}{A_s p_a}, \frac{\dot{m}_a}{\dot{m}_w}, \eta_d\right) = 0 \qquad (12)$$

as the dimensionless functional relationship. The reciprocal of the third term, Π_3, is the water spray momentum transfer relationship previously discussed above and used for modeling unconfined sprays and water-powered scrubbers. With fan-powered scrubbers the air velocity in the scrubber can approach and be greater than the average spray droplet velocity out of the nozzle, making the differential velocity, ΔV, in this dimensionless factor change from positive to negative. For one of the water-powered scrubber studies, using a supplemental fan in the wind tunnel facility demonstrated this effect by showing that scrubber capture efficiency dropped to a minimum and increased when the fan kinetic energy or air momentum overpowered the momentum transfer generated by the spray nozzle droplets (Jones and James, 1987). Therefore, this third term, Π_3, would be a confounding parameter, and its absolute value would have to be used for any water- and fan-powered scrubber empirical analysis.

As this empirical model includes both water- and fan-powered scrubbers, the model will focus on the known quantified variables of p_w, p_a, $\dot{m}_a$ and $\dot{m}_w$, commonly measured in both water- and fan-powered scrubbers studies used in this analysis. This functional relationship can be reformulated by recombination of the original dimensionless parameters in Eq. (12) and solving for the fifth dimensionless parameter of airborne dust capture efficiency, η_d. For this solution, the original parameters can be inverted, squared and/or multiplied by the other parameters into alternative dimensionless parameters.

The equation:

$$\eta_d = f_1\left(\frac{L_S}{\sqrt{A_S}}, \frac{p_w \dot{m}_a}{p_a \dot{m}_w}, \left|\frac{A_s p_a}{\dot{m}_w \Delta \mathrm{V}}\right|, \frac{\dot{m}_a}{\dot{m}_w}\right) \quad (13)$$

illustrates this particular functional solution, f_1, by multiplying the second parameter by the fourth parameter and taking the reciprocal and absolute value of the third parameter, while solving the equation for the fifth airborne dust capture efficiency, η_d, parameter.

The ratio of the product p_w times $\dot{m}_a$ divided by the product p_a times $\dot{m}_w$ will be the key independent variable empirically modeled by regression analysis because this dimensionless parameter had the greatest association with dust capture efficiency. In order to include the unconfined water and air atomized sprays previously tested into the model, the total air pressures generated inside the airflow measurement test apparatus, described in Pollock and Organiscak (2007), were subsequently measured with a Dwyer model 616WL-14-LCD, 0 to 249 Pa (0 to 1 in. wg) differential pressure transmitter (Dwyer Instruments Inc., Michigan City, IN). The total air pressure measurements for the un-confined water sprays were highly variable at the lower limits of detection for the instrument, usually less than 1.24 Pa (0.005 in. wg). The air-atomized sprays induced lower airflow quantities of less than 0.28 m^3/s (600 cfm) at some of the lowest total air pressures, averaging 0.249 Pa (0.001 in. wg) for the unconfined sprays measurements when operating at equivalent water and compressed air nozzle pressures of 172 and 345 kPa (25 and 50 psig). Unconfined water sprays induced higher amounts of airflows of greater than 0.28 m^3/s (600 cfm) and had slightly higher total air pressure measurements, averaging 0.458 Pa (0.002 in. wg) at 552 kPa (80 psig) and 0.747

Pa (0.003 in. wg) at 1,103 kPa (160 psig). These average air pressures were used in the modeling analysis of unconfined sprays.

The information used in developing these empirical models was collected from the averages of the replicated data for each spray and scrubber condition studied. The rationale for using the averages was to equally weigh each spray or scrubber test condition in the model, because the number of test replicates varied between the research studies shown in Table 1. Coal dust capture efficiencies in these studies were based on respirable gravimetric sampling measured by impactors described in Divers and Janosik (1978, 1980), Grigal et al. (1982) and by coal mine personal dust sampling units and real-time aerosol units described in Organiscak and Pollock (2007), Pollock and Organiscak (2007), Organiscak (2014) and Klima et al. (2017). Any dust efficiency test data using an atypical wet scrubber configuration — such as no water, zero water pressure, mist eliminator upstream of the wetted fan — were excluded from this empirical model analysis. Additionally, any tests where scrubbing area could not be adequately quantified — that is, in the USBM venturi scrubber tests — to determine scrubber air velocity pressures were excluded from the analysis. Finally, the empirical models were devised using IBM SPSS Statistics (IBM, Armonk, NY) and Excel Data Analysis (Microsoft, Redmond, WA) software, and the models are limited to their turbulent and incompressible scrubber airflow test conditions.

Results and discussion

Results for the two-variable regression analysis for the variable X_1 (ΔV) and the variable $X_2\left(\dot{m}_a/\dot{m}_w\right)$ with respect to airborne respirable dust capture efficiency, $\hat{Y}\left(\eta_d\right)$, of water-powered scrubbers and unconfined sprays are shown in Table 3 and Fig. 2. The empirical regression model is a good fit with an R^2 of 0.873 with regression coefficients being statistically significant at the 95 percent confidence level (p-values << 0.05). The regression coefficient β_1 for the variable X_1, or ΔV, is different between these empirical models because SI units of meters per second and United States customary system (USCS) units of feet per second were used in their analyses. Although these are good regression models, they do not include fan-powered wet scrubbers, and they require different equations for the ΔV units of measure. Therefore, the dimensionless analysis empirical model is more desirable in that it can be universally used for the different units of measure.

The relationship for the regression analysis of the dimensionless factor and the respirable airborne dust capture efficiency is shown in:

$$\eta_d = 1.504 - 0.081\, ln\left(\frac{p_w \dot{m}_a}{p_a \dot{m}_w}\right) \quad (14)$$

Figure 3 shows the fitted line for this regression equation with an R^2 of 0.903 and a standard error, s, of 0.101. Both the regression constant and slope parameters are significant at the 95 percent confidence level (p-values << 0.05). Although there is some scatter in the data for the regression model, it is a reasonably good fit and it spans the whole spectrum of wet collection of airborne respirable dust. The lower right group of points are the unconfined sprays, water and air atomized. The lower part of this group are the water spray nozzles and the four higher points in this group are the air atomized spray nozzles. The middle points in the graph are the water-powered scrubber data and the upper top left points in the graph are the fan-powered scrubber data. Most of the scatter in the data points for the fan-powered scrubbers are due to the different collection mechanisms: flooded bed, venturi, brush, wetted fan and cyclonic. The flooded-bed and venturi scrubbers tended to have noticeably higher respirable dust capture efficiencies than the wetted-fan and cyclonic scrubbers (Divers and Janosik, 1978, 1980). This may be due to the wetted-fan and cyclonic scrubbers centrifugally removing some of the water droplets from the cross-sectional scrubbing area compared to the flooded-bed and venturi mechanisms, which try to maximize the droplet dust interaction in their scrubbing areas.

Additionally, different spray types — hollow-cone, full-cone, flat-fan, steady stream from small pipe — and numbers of nozzles were used in both the water-powered and fan-powered scrubber testing, which most likely contributed to some of the spread in this model of the data. Spray types can generate notably different droplet sizes and velocities at comparable water pressures (Pollock and Organiscak, 2007). Other dimensional analysis can be conducted to include some of these other physical variables, such as the dust size and water droplet size, given that this information is measured or available for the modeled experiments. As only respirable-sized dust efficiency measurements were used in this analysis, the impact of dust size on airborne capture efficiency is anticipated to be minimal and was not included in this model. However, the simplified empirical model as shown in the developed Eq. (14) does span the whole spectrum of wet collection of airborne respirable dust and permits examination of changes to the basic wet collection model parameters.

An example of this type of examination can be observed using the air-to-water mass flowrate ratio, $\dot{m}_a/\dot{m}_w$, in Fig. 4. This analysis used the airborne dust capture laboratory data measured while altering the number of BD3 hollow-cone water sprays (Spraying Systems Co., Wheaton, IL) from two to 11, operating at 1,379 kPa (200 psig) on the top- or under-boom side of the model mining machine in Jayaraman, Schroeder and Kissell (1986). Water flows and airflows were converted to mass flowrates using their densities at standard air and temperature. The ventilation airflow was typically studied at 1.51 m^3/s (3,200 cfm), but was varied during several of the tests from 0.47 to 2.12 m^3/s (1,000 to 4,500 cfm). The open blue points are the data from these experiments and the red crosses represent the modeled data of Eq. (14), assuming the total air pressure of the exhaust face area with open sprays, p_a, was 1.24 Pa (0.005 in. wg). The total air pressure across the face was estimated from the sum of the pressure losses at the face using the Atkinson equation for a smooth-lined, moderately obstructed, high-degree-of-entry curvature and calculated velocity pressures (Hartman, 1961). This modeled relationship similarly supports the experimental data with an increase in dust capture efficiency from right to left for an increasing number of water sprays on the continuous mining machine.

Figure 4 also shows the model (black points) for a wet fan-powered scrubber, Eq. (14), at the same air-to-water mass flowrate ratios while operating at 1,245 Pa (5 in. wg) of total scrubber air pressure, p_a. Five inches, or 1,245 Pa, of total pressure is where many of the fan-powered scrubbers exceed 80 percent respirable dust capture efficiency, depending upon air-to-water mass flowrate ratio (Divers and Janosik, 1978, 1980). As illustrated in Fig. 4, the fan-powered scrub-ber would make the largest difference in airborne dust capture with the air-to-water mass flowrate ratio having a lesser effect. This drastic improvement between mining machine mounted sprays versus a flooded-bed scrubber has been independently observed in laboratory and underground studies (Colinet and Jankowski, 1998; Colinet, Reed and Potts, 2013; Organiscak and Beck, 2014). Although this empirical model can generally be used to examine the airborne dust capture effects of changing one or several of the variables while holding the others constant, in reality changing one of these variables for a particular spray or scrubber system may influence changes in another variable of the model. This model only applies to airborne respirable dust capture and excludes the dust control effects of wetting the product.

Conclusions

Initially, the relative water droplet-to-airflow velocity and mass airflow-to-water flow ratio variables of water sprays and water-powered scrubbers were analyzed for airborne dust capture. Multiregression analysis of these two factors had a significant relationship, R^2 = 0.873, with airborne respirable dust capture efficiency. Additionally, a dimensional analysis was conducted on other key engineering measures to include all forms of water spray and fan-powered wet scrubbers with the intent of formulating a comprehensive model for examination of these parameters for the design of wet dust collection systems. A significant linear logarithmic relationship was found between a dimensionless factor, R^2 = 0.903, and airborne respirable dust capture efficiency. This dimensionless factor was a ratio made up of the product of water pressure and mass airflow rate, divided by the product of the total scrubber air pressure and mass water flow rate. The logarithmic regression model of this dimensionless factor can be used to examine the airborne respirable dust capture of water sprays and fan-powered scrubbers. Either SI or USCS units can be used in this empirical model as long as the pressure or mass units are consistent and dimensionless. This empirical model provides an analytical tool for examining several key water spray and wet scrubber design parameters related to airborne respirable dust capture efficiency. It is intended to assist with dust control system design for controlling mine worker dust exposure and reducing their risk of contracting occupational lung diseases.

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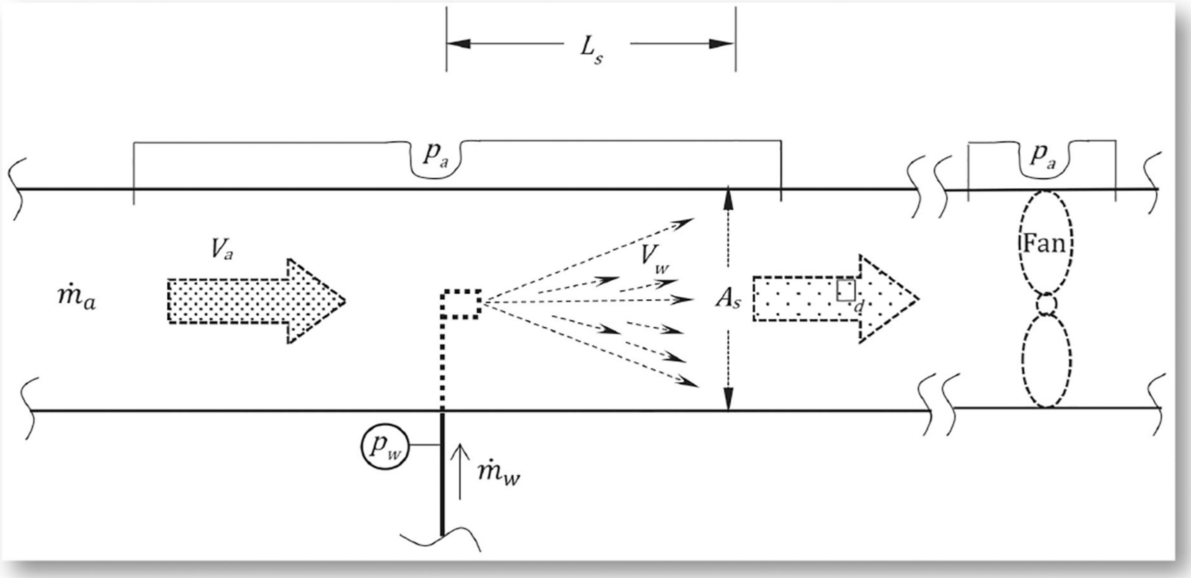

Figure 1.

Two-dimensional schematic of water- or fan-powered scrubber capturing dust from the air, illustrated with key operating variables.

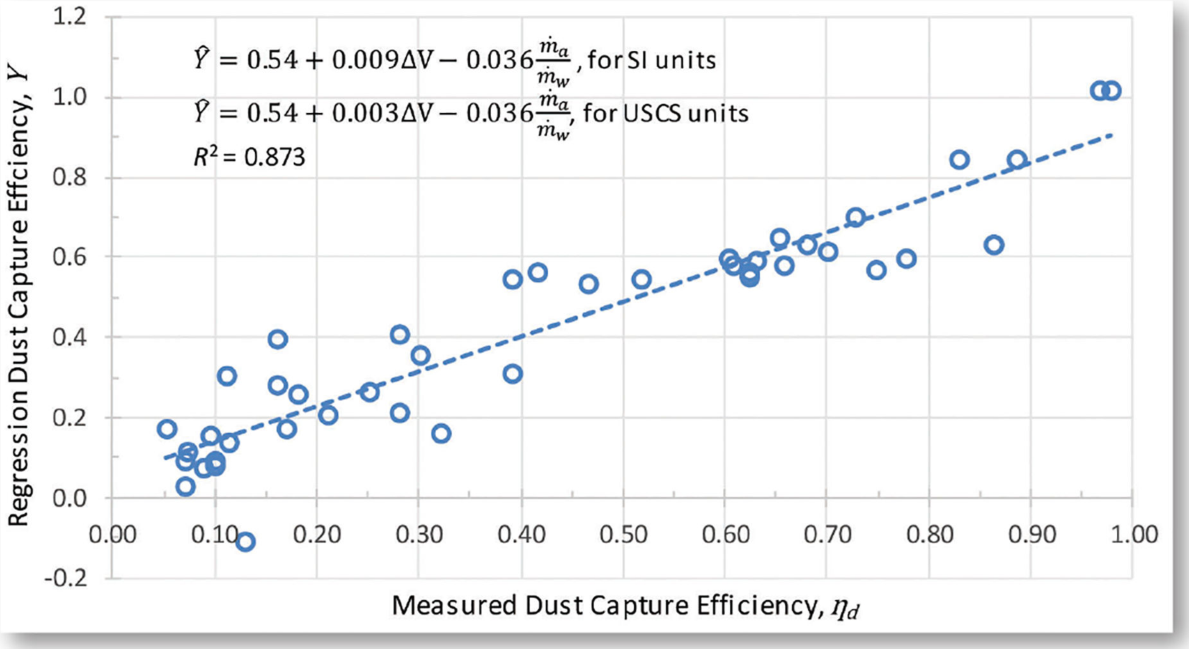

Figure 2.

Measured versus regression predicted dust capture efficiency.

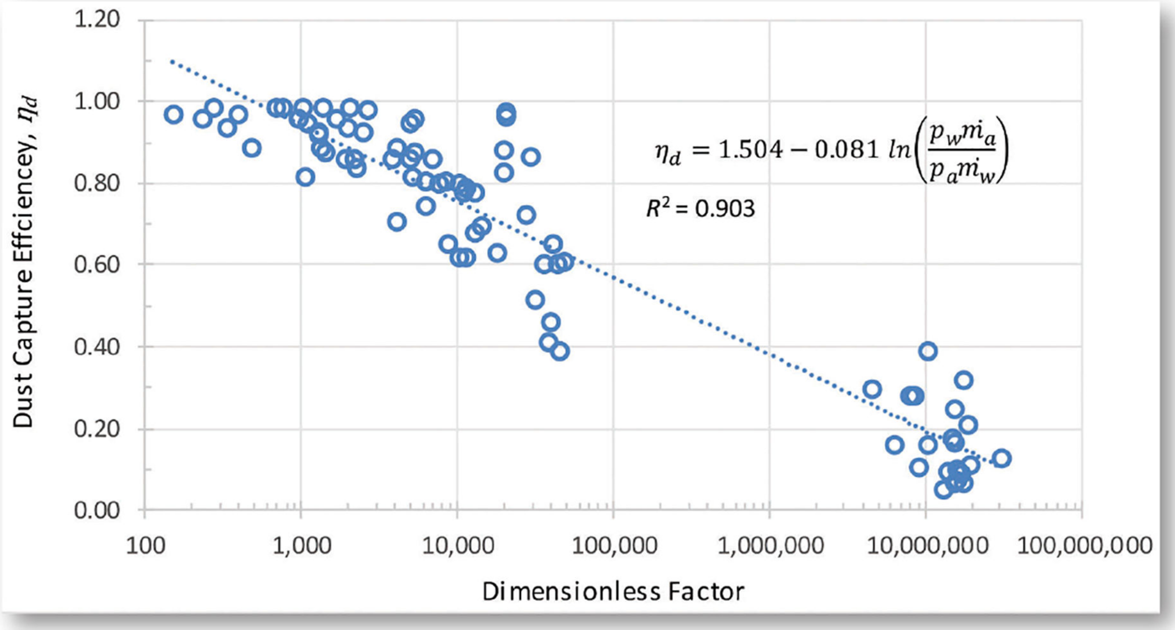

Figure 3.

Relationship between dust capture efficiency and the dimensionless factor for sprays and wet scrubbers.

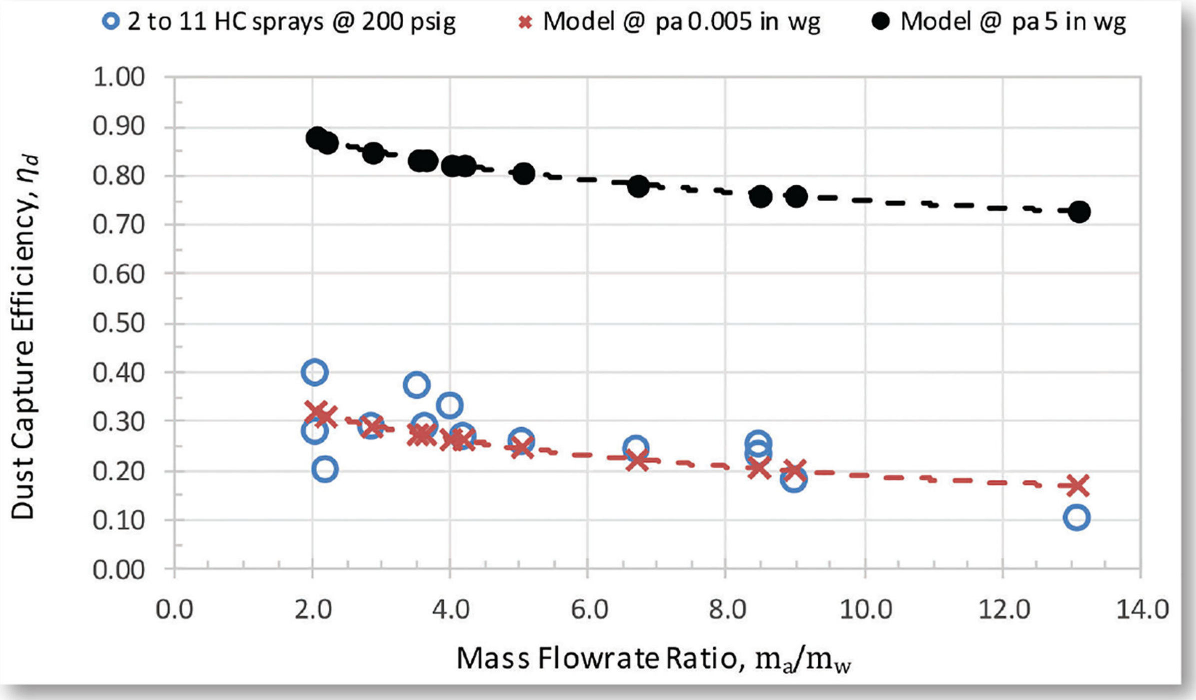

Figure 4.

Airborne dust capture efficiency data and modeling with respect to air-to-water mass flow ratio.

Table 1

Research study data used for the empirical modeling of water spray and wet scrubbers.

Study reference	Experimental parameters tested	Experimental data measured
Klima et al. (2017)	• 60° self-cleaning hollow-cone spray versus 76° and 77° typical hollow-cone spray nozzle designs. • Unconfined spray configuration. • At two comparable orifice sizes or flow rates. • At 552 kPa spray operating pressure.	• Spray operating pressure. • Water flow quantity. • Spray induced airflow quantity. • Airborne respirable dust capture. • Spray operating air pressure.[a]
Organiscak (2014)	• 77° hollow-cone spray. • Unconfined spray configuration. • Three wetting agents. • 552 and 1,103 kPa spray operating pressures.	• Spray operating pressure. • Water flow quantity. • Spray-induced airflow quantity. • Airborne respirable dust capture. • Spray operating air pressure.[a]
Pollock and Organiscak (2007)	• Hollow-cone, full-cone, flat-fan and air-atomized sprays. • Unconfined and confined spray configurations. • 552 and 1,103 kPa spray operating pressures. • 172 and 345 kPa atomized spray operating pressures.	• Spray operating pressure. • Water flow quantity. • Spray induced airflow quantity. • Airborne respirable dust capture. • Spray operating air pressure.[a]
Organiscak and Pollock (2007)	• 33° and 81° hollow-cone spray angles. • One to three sprays in series inside a 6-in.-diameter pipe. • 552, 1,103 and 1,655 kPa spray operating pressures. • 5.1-, 12.7- and 20.3-cm demister impaction plate distances.	• Spray operating pressure. • Water flow quantity. • Induced scrubber airflow quantity. • Scrubber operating air pressure. • Airborne respirable dust capture.
Grigal et al. (1982)	• 25° and 40° flat-fan spray angles. • Six coplaner sprays in a rectangular duct measuring 30.5 by 61 cm. • 1,724 and 3,448 kPa spray operating pressures.	• Spray operating pressure. • Water flow quantity. • Induced scrubber airflow quantity. • Scrubber operating air pressure.

Study reference	**Experimental parameters tested**	**Experimental data measured**
		• Airborne respirable dust capture.
Divers and Janosik (1980)	• Venturi and flooded-bed scrubber configurations. • 241 to 965 kPa spray operating pressures. • 7.9 to 36 L/min water flow rates. • Scrubber cross-sectional area dimensions. • Scrubber airflow varied from 0.87 to 1.89 m^3/s. • With and without droplet eliminator.	• Spray operating pressure. • Water flow quantity. • Scrubber fan operating air pressure. • Airborne respirable dust capture.
Divers and Janosik (1978)	• Flooded-bed, cyclone, wetted-fan and wetted-brush configurations. • 138 to 965 kPa spray operating pressures. • 1.9 to 22 L/min water flow rates. • Scrubber cross-sectional area dimensions. • Nearly constant airflow of 0.83 to 1.13 m^3/s. • With and without droplet eliminator.	• Spray operating pressure. • Water flow quantity. • Scrubber fan operating air pressure. • Airborne respirable dust capture.

[a] Operating air pressures of the unconfined sprays were recently and independently measured after the original study.

Table 2

Relevant variables used in Buckingham Pi analysis and their corresponding dimensions.

Variable	**Description**	**Dimensions**
A_s	Scrubber cross-sectional mixing area.	L^2
L_S	Length of the spray mixing area.	L
p_w	Water spray operating pressure.	$ML^{-1}T^{-2}$
p_a	Scrubber total air pressure (measured across water-powered scrubber or fan).	$ML^{-1}T^{-2}$
ΔV	Mean differential velocity between spray water droplets and scrubber airflow.	LT^{-1}
$\dot{m}_w$	Mass flow rate of spray water.	MT^{-1}
$\dot{m}_a$	Mass flow rate of scrubber air.	MT^{-1}
η_d	Airborne dust capture efficiency.	Dimensionless

Table 3

Two-variable linear regression analysis statistics for unconfined sprays and water-powered scrubbers.

Regression statistics for $\hat{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2$	**In SI units for** ΔV **(m/s)**	**In USCS units for ΔV (ft/s)**
Regression, R^2	0.873	0.873
Standard error, s	0.106	0.106
Number of observations, n	43	43
Regression intercept, β_0 (p-value)	0.540 ($p \ll 0.05$)	0.540 ($p \ll 0.05$)
Variable X_1 regression coefficient, β_1 (p-value)	0.009 ($p \ll 0.05$)	0.003 ($p \ll 0.05$)
Variable X_2 regression coefficient, β_2 (p-value)	−0.036 ($p \ll 0.05$)	−0.036 ($p \ll 0.05$)