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RESEARCH INTO THE SELECTION AND EFFICIENCY OF NOZZLES FOR AIRBORNE DUST SUPPRESSION

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ABSTRACT: The suppression of airborne dust is a significant issue within the resources industry that has been highlighted by the re-emergence of lung diseases such as coal workers' pneumoconiosis and silicosis. A prominent method for the control of airborne dust is the use of water spraying systems to suppress dust and minimise its liberation into the workplace. The challenge with water spraying systems for airborne dust suppression lies largely in the correct selection of nozzles to suit the application. This paper outlines work conducted by the University of Wollongong with funding from the Coal Services Health & Safety Trust to investigate the factors affecting the performance of water spraying dust suppression systems. Through this project, an innovative experimental apparatus was setup for the testing of nozzles under various dust and airflow conditions. This allowed for a parametric study to be conducted on the influence of factors such as water flow rate and pressure, droplet size, dust concentration, and dust velocity to be investigated. The outcome of this study was the introduction of an equation to compute a spray parameter based on droplet size, water flow rate, and spray velocity that can be used for the selection of nozzle for airborne dust suppression. Comparison between the computed spray parameter with the large number of tests conducted allowed for recommendations to be made that will aid in the selection of nozzles for airborne dust suppression systems using water sprays in the future.

INTRODUCTION

The suppression of airborne dust continues to be an issue for the resources industry, and particularly with increasing regulatory focus on particulate matter there is a need to improve practices. In most parts of the global mining industry, lung disease continues to exist despite the development of mine management systems and dust control technologies that reduce the risk. The incurable disease, pneumoconiosis, was thought to have been eliminated in the 1980s in Australia, however, coal workers' pneumoconiosis (CWP) from the coal mining industry has been thrust back into the spotlight following the diagnosis of a Queensland miner with CWP in 2015 (Penrose, 2020). As well as CWP, silicosis, another dust related disease of the lung, has recently become more prevalent; a report prepared by the Australian government's national dust disease task force estimated that nearly one in four workers exposed to respirable crystalline silica dust from engineered stone before 2018 have been diagnosed with silicosis (Kelly *et al.*, 2021). This increase in the occurrence of dust related lung diseases has resulted in the resources industry facing tremendous pressure to improve their dust control strategies. This has prompted the perusal of new and innovative methods of dust control with a focus on quantifiable methods.

Water sprays are one of the most commonly used airborne dust suppression systems, however, they often suffer from poor capture efficiency. This can largely be attributed to the fact that the current ability for designers to take an engineering approach to the control of dust is severely limited by the lack of reliable design methodologies and available data (Roberts *et al.*, 2016). For example, the dust suppression efficiency of a spraying system cannot be predicted accurately before a system is installed and operated on site. However, other traditional cleaning technologies, such as the bag house and the electrostatic precipitator, have established methods to predict dust capture efficiency at the design stage, which greatly assists engineers in the design of the corresponding dust control system.

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This paper outlines the development of a method for testing dust capture effectiveness of a spray nozzle and the results collected across a variety of different nozzles tested. The outcome is a novel method that engineers can use for selecting nozzles for airborne dust suppression systems and predicting their performance. This work was completed as part of a larger project funded by the Coal Services Health & Safety Trust entitled “Evaluation of the Performance of Water Spraying Dust Suppression Technology within the Coal Mining Industry” (Roberts *et al.*, 2022), the full report can be accessed on the Coal Services website.

SPRAYING SYSTEMS FOR DUST SUPPRESSION

A spraying system can control the dust by direct spraying (wetting) the bulk material to prevent dust from becoming airborne or by spraying the airborne dust cloud and causing the particles to collide, agglomerate and fall from the air; the focus of this paper is airborne dust suppression by spraying.

A spraying system is quite easy to install and maintain and as such it is commonly used in the resources industry. However, the dust suppression efficiency of a water spraying system when it comes to airborne dust suppression can vary greatly depending on the system design. A typical ROM bin is shown in **Figure 1**, where a coarse droplet spray system is shown on the left and a fine droplet system on the right. The coarse droplet system was found to be completely ineffective whilst having four times the water consumption of the highly effective fine droplet system. This highlights the need for better methods of selecting spray nozzles for airborne dust capture to achieve the most efficient and effective airborne dust suppression.

Figure 1: Example of a typical ROM bin with coarse (left) and fine (right) droplet spraying systems (Roberts and Wypych, 2017)

The capture mechanisms of airborne dust suppression using sprays includes collision and condensation. The collision mechanism occurs when the spray drop collides with dust particles and the particle-drop agglomerate then deposits to the floor or is otherwise collected by the surface of objects nearby (Cheng, 1973). The condensation mechanism occurs when a droplet’s phase changes; the droplet, especially with fine droplets, will evaporate to vapor which extends the relative humidity above 100% and the water then condenses directly onto the dust particles. In this way, particles can be made to grow to a size where they will either fall out of suspension or be removed by a spray (Schowengerdt and Brown, 1976). The collision of droplets and particles can be caused by inertial impaction, interception and/or Brownian diffusion (Cooper and Alley, 2002). When a flowing fluid approaches an object, such as a droplet or a steel wire, the flow lines will diverge around that object, as shown in **Figure 2**. Inertial impaction may occur when a particle does not follow the flow stream because of its inertia resulting in impact with the object. Interception occurs when a small particle with low inertia may follow the streamline and tend to pass the object, but it strikes the object because its radius is larger than the distance between the surface of the object and the streamline. When a particle is sufficiently small, collisions with random air molecules involve momentum changes which are not entirely negligible compared with the drag force or gravity of the particle; as a result, the particle exhibits random motions, known as Brownian motion which may result in impaction with the object. Considering these mechanisms, inertial impaction plays an important part in the capture of particles larger than 5.0μm, while Brownian diffusion is essential for capture of smaller particle less than 0.5μm (Kim *et al.*, 2001).

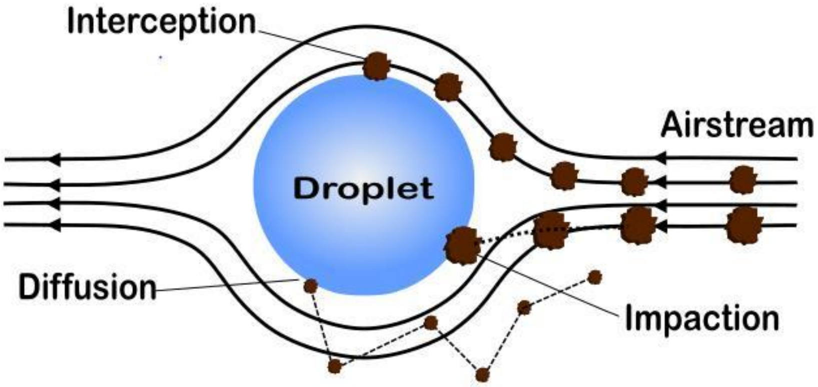
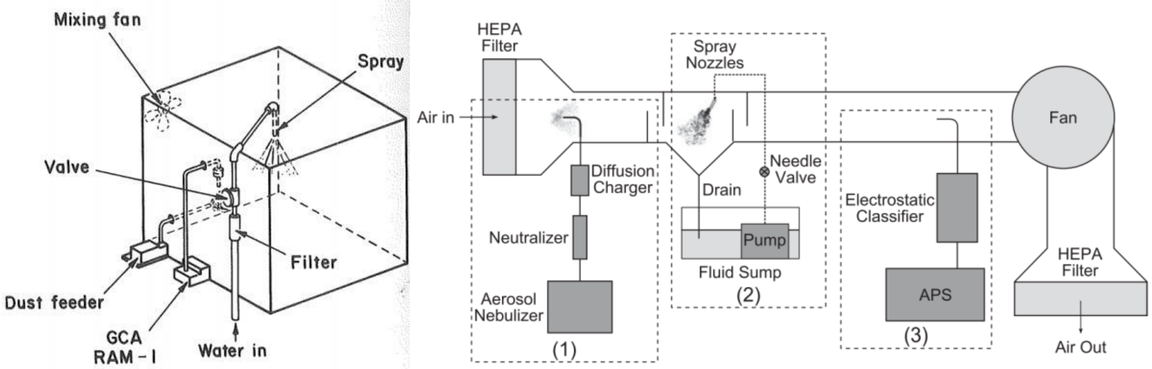


Figure 2: Particles colliding with droplet (Liao *et al*., 2020)

The factors related to dust capture efficiency include the characteristics of the spray and dust in combination with the local ambient conditions (Wypych and Mar, 2013). The characteristics of a spray which may impact on its capture efficiency include the orientation and position of the spray, water pressure, droplet size and speed. Ambient conditions, such as humidity and cross wind (Roberts *et al*., 2018) can also affect spray dust suppression efficiency.

In previous studies, experimental test rigs or facilities (e.g. **Figure 3**), such as wind tunnels (Tessum and Raynor, 2017; Zhou *et al*., 2017), dust boxes (McCoy *et al*., 1985; Grundnig *et al*., 2006), and industrial models (Jayaraman and Jankowski, 1988; Seaman *et al*., 2020), have been employed to evaluate the performance of sprays with plain water or additives. However, it is inconclusive as to whether the results generated from these test rigs or facilities can be applied to other industrial applications. There are also some inherent limitations and potential issues with these test rigs, such as the limited ability for a spray to be fully developed before impacting the walls of the test rig, and the complete enclosure of the spray and dust within the test rig potentially forcing the dust to pass through the spray where it may otherwise have gone around. As such there is a need for a test that can represent the more general case of a spray capturing a dispersed airborne dust similar to that occurring due to general material handling operations, such as from conveyor transfers or truck dumping.



(a) (b)

Figure 3: Experimental test rigs, (a) Dust box (McCoy *et al*., 1985), (b) Wind tunnel (Tessum and Raynor, 2017)

SPRAY DUST CAPTURE TEST RIG

This project has looked to address some of the limitations of existing test rigs presented in literature through the development of a new apparatus, as shown in **Figure 4**. The test rig consists of a push-pull fan system where dust is injected at one end and passed through a duct where the concentration is measured prior to the spray zone, an open section allows a spray to be operated for dust capture to occur and on the other side a receiving duct draws any remaining dust in and allows the concentration to again be measured. The difference between the two dust concentration measurements represents the dust captured by the spray and allows for the dust capture performance of the spray to be evaluated. Dust is fed into the system via a vibratory feeder connected to venturi air pump, this allows the dust concentration to be varied based on the speed of the feeder. The velocity of the dust is controlled using variable speed controllers connected to each fan. Dust sampling utilised a variable flow air pump connected to a modified IOM sampler with an isokinetic sampling probe. The isokinetic probe minimises potential sampling bias by ensuring a consistent flow field within the duct and probe. The air velocity within the system is controlled through variable frequency drives connected to each fan. To verify the flow within the ducts, the air velocity was measured along the plane where the dust sampling probes would be located. The number and location of measuring points for both air velocity and dust concentration were determined in accordance with AS 4323.1(2014). The standard recommends measuring four points on a 142mm PCD for a round duct with 200 mm diameter. However, the velocity and concentration at the centre of the duct is also measured to compare with the average of the recommended points. The nominal velocities tested for each duct were 4m/s and 8m/s on the discharging side and 8m/s and 12m/s on the receiving side. The receiving duct is operated at a higher velocity to achieve an effective entrainment zone for dust extraction. All air velocities were measured using a hot wire anemometer.

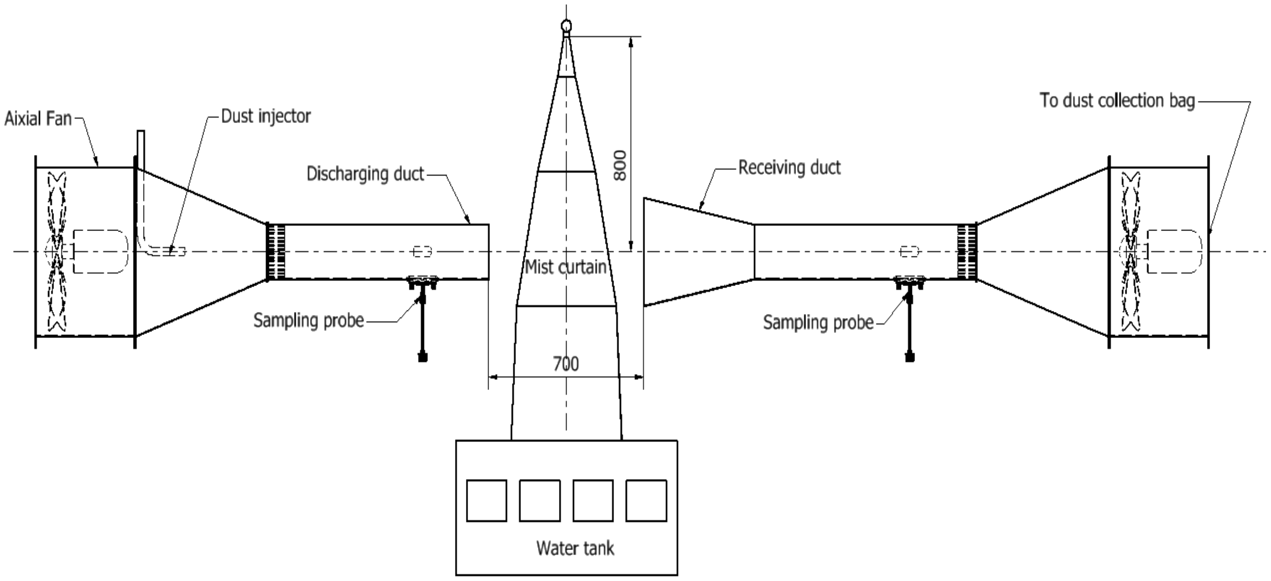


Figure 4: UOW dust capture efficiency test rig

DUST CAPTURE TEST RESULTS

The test rig developed provides the opportunity to evaluate the performance of various nozzles commonly used for air borne dust suppression to provide key insight into the selection of these nozzles. The study includes an investigation of 12 different nozzles and 37 different operating conditions. The results of the testing completed is given in **Table 1**. The influence of flow rate, operating pressure, dust concentration and dust velocity relative to the spray characteristics were all considered.

Influence of spray flow rate

The availability of the EM.GIZ.XX (EnviroMist) style nozzles of identical design but with four different orifice sizes allowed for the influence of water flow rate to be investigated independently of operating pressure. **Figure 5** shows the change in dust capture performance for the EnviroMist nozzles as the orifice size increased from 0.6mm up to 2.0mm; there is a clear increase in dust capture with the increasing flow rate as a result of the larger orifice size. Given that all the nozzles were operated at the same pressure (≈4-5 bar) and that droplet size is mainly a function of pressure (viz. droplet size should be similar for all) then this result implies that the dust capture efficiency is strongly influenced by the number of droplets. This conclusion makes logical sense but quantifying the result also allows for further investigation of these factors to be undertaken.

Table 1: Dust capture efficiency test results

Nozzle ID	Pressure (bar)	Concentration (mg/m^3)	Dust Velocity (m/s)	Dust Reduction (%)
EM.GIZ.06	4	1000	4	49.2
EM.GIZ.06	60	1000	4	94.3
EM.GIZ.06	4	500	4	52.9
EM.GIZ.06	20	500	4	91.3
EM.GIZ.06	60	500	4	95.6
EM.GIZ.06	100	500	4	96.9
EM.GIZ.06	20	500	8	85.2
EM.GIZ.06	60	500	8	93.4
EM.GIZ.06	100	500	8	96.9
EM.GIZ.08	20	500	4	93.4
EM.GIZ.08	60	500	4	96.7
EM.GIZ.08	100	500	4	97.8
EM.GIZ.08	60	1000	4	95.4
EM.GIZ.10	4	1000	4	74.8
EM.GIZ.10	4	500	4	77.8
EM.GIZ.10	60	500	4	93.7
EM.GIZ.15	4	1000	4	88.7
EM.GIZ.15	4	500	8	81.3
EM.GIZ.20	4	1000	4	93.1
EM.GIZ.20	4	500	8	86.2
GG 3	4	500	4	91.2
GG 3	6	500	4	93.3
GG 3	10	500	4	94.1
GG 3	4	500	8	87.0
GG 3	6	500	8	91.8
GG 3	10	500	8	92.9
DCM1370	2	1000	4	17.8
DCM1370	2	500	4	11.2
DCM1370	4	1000	4	84.6
RXT1166	4	1000	4	67.5
RXT1166	15	1000	4	93.4
ST33	W3 A4	500	4	96.8
ST33	W3 A4	500	8	91.3
FF	4	500	4	85.5
FF	4	500	8	74.8
FF	6	500	8	83.4
FF	10	500	8	86.2

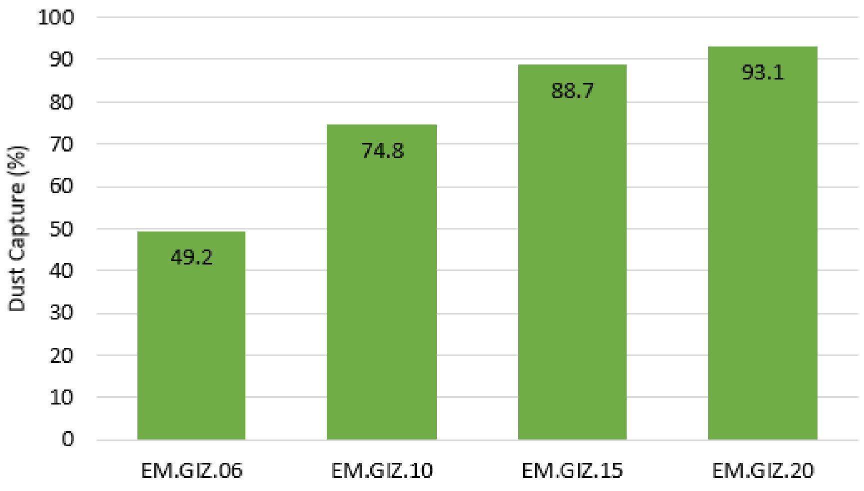


Figure 5: Dust capture performance of various size EnviroMist nozzles operated at mains water pressure (≈4-5 bar)

A similar test was conducted with the nozzles operated at a higher pressure (60 bar), however, this resulted in high dust capture efficiency (>90%) for all the nozzles tested and as such the result is less conclusive. The result of this is shown in **Figure 6**, where the differences are within the margin of error for the overall test method and suggests that the influence of increasing water flow rate diminishes with increasing pressure.

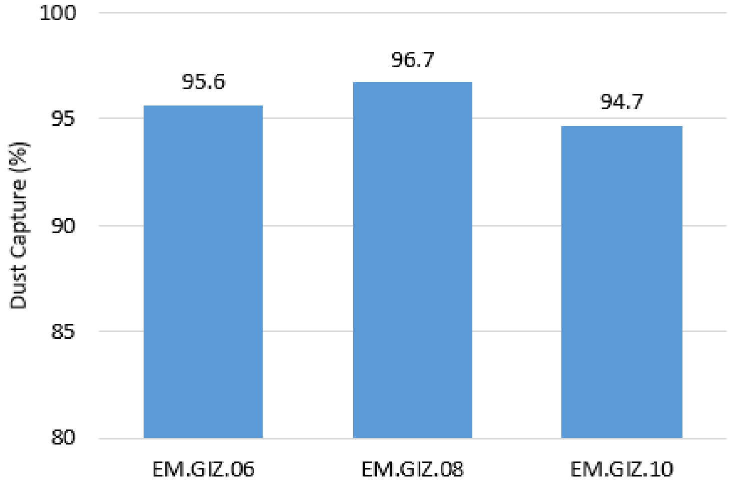


Figure 6: Dust capture performance of various size EnviroMist nozzles operated at 60bar water pressure

Influence of nozzle operating pressure

The effect of adjusting the pressure has been investigated for most of the nozzles tested. **Figure 7** shows the effect across four different nozzles studied in the project, in all cases the dust capture performance increases with pressure. This shows that the performance of a dust suppression system can generally be improved by operating at a higher pressure, however given the performance of each nozzle is different at each pressure, it is not possible to determine the optimum pressure for a system without already having the data. The reason for the improved dust capture performance with increasing pressure cannot be determined as yet. From the analysis, it is clear that an increased flow rate will improve dust capture, which will account for at least some of the improved performance occurring when pressure is increased. However, droplet size is also a function of pressure which means not only is the flow rate increasing but the droplet size is also getting smaller, leading to a greater number of droplets in the spray as a result of both aspects. It is quite likely that the dust capture performance is not a function of just droplet size or flow rate but the combination of the two producing the greatest droplet concentration with a droplet size effective for dust capture.

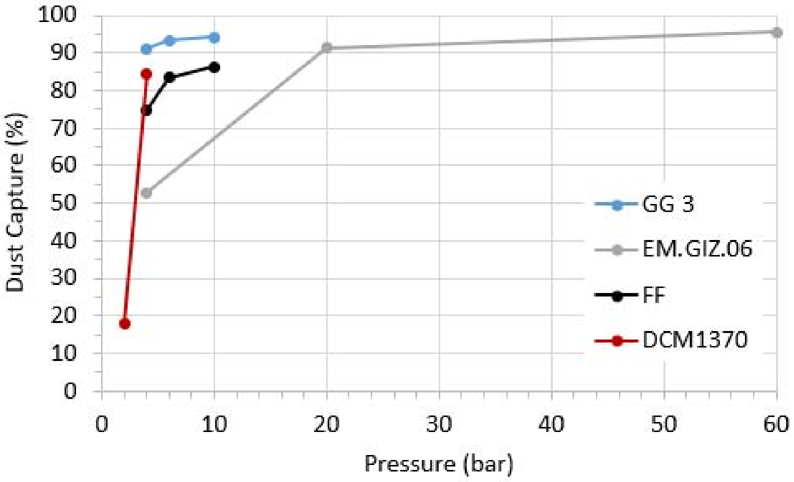


Figure 7: Dust capture performance of various nozzles at multiple pressures

Influence of dust concentration on dust capture performance

The influence of dust concentration on the dust capture performance of a spray is another important factor to understand. The test rig developed for the study allowed for dust concentrations up to approximately 1000mg/m^3, where the maximum concentration was a limitation of the feeder and filtration system used. To understand the influence of dust concentration, tests were conducted with nominal concentrations of 500mg/m^3 and 1000mg/m^3. The results generated from these tests were unfortunately inconclusive, five nozzles/pressure combinations were tested at the two concentrations with four of the configurations resulting in lower performance at higher dust concentration, but one did not. The average reduction in performance of the four nozzles with lower performance was 2.32% which is not significant and lies within the margin of error for the experiment. The configuration that did not produce a lower performance with higher concentration had a dust capture of 11.2% at 500mg/m^3 and 17.2% at 1000mg/m^3. It is likely that the variation is due to the overall very low performance of the spray in this configuration which creates a higher margin of error. The relatively low concentration generated in the test compared to the extremes of what is found in industry is likely the main reason for not finding a significant difference. Although all of the measurements directly made as a part of this project were within the capability of the test rig, it is common to find dust concentrations more than 100 times greater than what is possible using the test rig. For example, dumping coal into a ROM bin is likely to have concentrations >100g/m^3 TSP. Based on this, UOW intends to continue this aspect of the research through further development of the current test rig to allow testing of concentrations of at least 100g/m^3.

Influence of dust cloud velocity on dust capture performance

The influence of dust cloud velocity on dust capture performance is another important aspect given that every application will have different dust and wind velocities that need to be accounted for. To investigate this, ten nozzle/pressure combinations were tested at 4m/s and 8m/s. The velocities were chosen to be representative of the findings from industry detailed in the main project report (Roberts *et al.*, 2022). Across the twenty configurations tested, the average dust capture performance was 4.6% lower when the dust cloud velocity was 8m/s compared to 4m/s with the maximum difference being 10.7%. The results show that for the nozzles tested, there is a clear reduction in performance with higher dust cloud velocity. The reason for the change is dust capture with the increasing dust cloud velocity is most likely a function of the spray velocity, where it is easier for a hole to be blown through a low velocity spray compared to a high velocity spray. This is an important finding that can be included in further analysis.

QUANTIFYING THE PERFORMANCE OF A SPRAY FOR DUST CAPTURE

From the data collected and outlined so far it is clear that there are many factors affecting the performance of a water spraying dust suppression system. This has been one of the long running difficulties with the design of these systems. To reduce the difficulty of designing these systems it is proposed that a means of quantifying a nozzle for dust capture performance should be developed. Based on the data outlined, it is clear that water consumption, droplet size and spray velocity all play a role in the effectiveness of a spray. Therefore, it is proposed to define a spray efficiency parameter that can be used for the evaluation of the potential performance of a spray for dust capture, this is given in Equation 1.

$$S_\eta = \frac{kQv}{D_{3,2}} \qquad \text{(Equation 1)}$$

where, k is a constant to convert S_η to a dimensionless parameter dependent on the units used, Q is the volumetric flow rate through the nozzle, v is the theoretical exit velocity of spray out of the nozzle, and $D_{3,2}$ is the Sauter mean diameter. This provides a single parameter that can be used to directly compare each of the tests conducted such that a better understanding of the results can be developed.

Figure 8 shows the spray parameter plotted against dust capture performance for all the tests conducted. Considering **Figure 8**, there are two clear zones present (indicated by the dotted red line) in the relationship between capture performance and the spray parameter. The first section of the plot shows a steep improvement in dust capture as the spray parameter increases from 0 up to a spray parameter of approximately 3 where the efficiency climbs above 80%. The second section shows a levelling out of the curve where the spray parameter needs to increase significantly for there to be an increase in capture performance. This is likely to be a valuable insight for designers of dust suppression systems as it can be used to improve the efficiency of a system being designed (or even operated). For example, a system designed to give a spray parameter of 100 is unlikely to perform significantly better than one with a spray parameter of 10, however it may have much higher water and/or energy consumption. Another example where this data may be useful is in the selection of spray for a continuous miner where the risk of dust and spray rolling back over the miner can be an issue due to the excessive turbulence generated by high energy sprays. In this scenario it is important to select a spray with good dust capture characteristics, but it cannot have excessive energy (high pressure) otherwise there is a risk of rollback. The spray parameter can also be used to aid in optimised selection of a nozzle's operating condition.

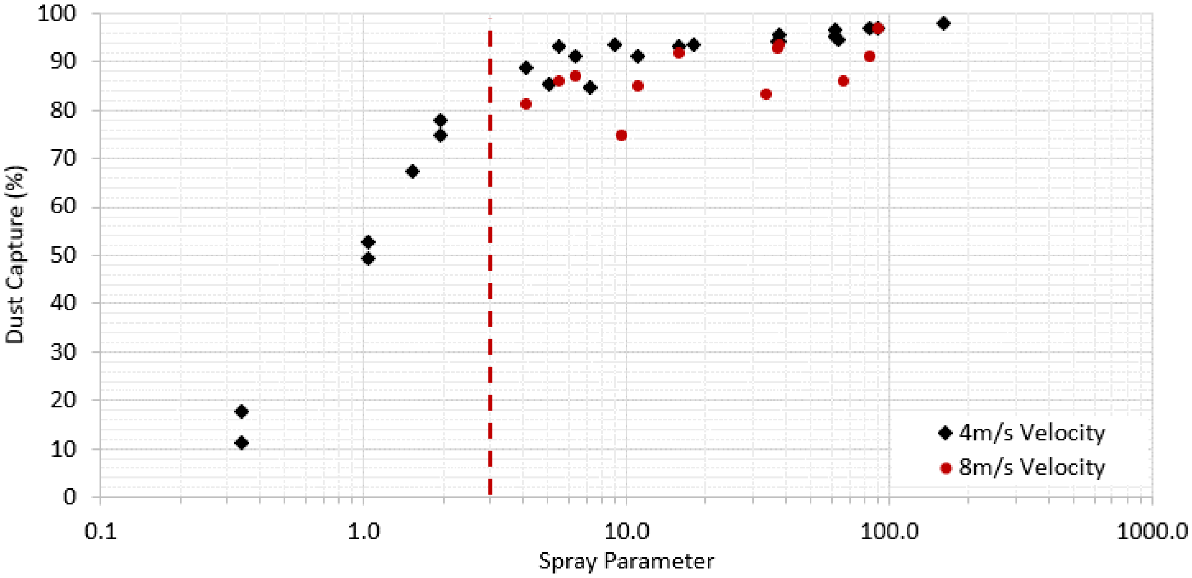


Figure 8: Dust capture performance vs. spray parameter for all tests conducted

Figure 8 also shows the variation in dust capture performance with 4m/s and 8m/s dust velocities where it is evident that there is an appreciable reduction in effectiveness at higher velocities. In this case, it is not until a spray parameter of 10 is reached that all data points show an effectiveness greater than 80%. Although the data set is still somewhat limited, the use of a spray parameter to aid in the selection of nozzles and their operating condition for airborne dust suppression shows great promise. Some recommendations can be made based on the results to date:

- A spray parameter of greater than 10 should be used for dust clouds up to 5m/s.
- A spray parameter greater than 50 should be used for dust clouds of 5-10m/s.
- Based on the data collected, these recommendations should result in at least 85% dust capture under the stated conditions and assuming the dust concentration is not significantly greater than that tested.

CONCLUSIONS

A significant challenge for engineers designing airborne dust suppression systems has been in the selection of the correct spray nozzle/s for the application. This project has led to the development of a spray efficiency parameter that presents a potential solution to this challenge and gives engineers greater confidence when designing these systems. Although further research should be conducted, the results to date provide a strong argument for the use of a spray efficiency parameter for nozzle selection. It must also be noted that this is only "one piece of the puzzle" and the design of an airborne dust suppression system also needs to take into account the broader application conditions, including any specific requirements or restrictions. As such, the work of this study should be combined with previous work to ensure spray systems are designed to provide not only a high theoretical capture efficiency but also ensure full coverage and sufficient spray energy to suit the application. Previous work has been conducted by UOW to aid in this through prediction of spray penetration in various cross winds (Roberts *et al.*, 2018) and through the simulation of sprays using computational fluid dynamics (Roberts *et al.*, 2021). Together this work provides a framework that engineers can use in the design of airborne dust suppression systems.

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