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Research, Development and Application of Dust Suppression Technology

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RESEARCH, DEVELOPMENT AND APPLICATION OF DUST SUPPRESSION TECHNOLOGY

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ABSTRACT: The coal industry faces significant challenges in the control of dust to meet emissions regulations and goals as well as ensuring sustainable operations. This paper describes some of the different techniques and innovative technologies that are being developed and implemented to improve the suppression of airborne dust, specifically through the use of high-energy micro-mist sprays. The utilisation of CFD modelling and simulation is identified and described as a key enabling technology for an improvement in dust suppression technology both from a level of understanding of the source and flow of dust emissions and for the development of new systems that can be used in the coal industry. CFD modelling is shown to be effective for modelling both spray dispersion and cross-wind effects allowing designers to develop high-efficiency dust suppression systems with a greatly improved level of confidence when compared to traditional techniques. New high-energy micro-mist technology is also outlined as a key element in developing high-efficiency dust suppression systems. Experimental results and industry applications are presented to demonstrate the significant improvements that can be achieved in suppressing or reducing airborne dust emissions.

INTRODUCTION

In the coal industry, dust emissions are an increasingly troublesome issue that has seen very little improvement achieved for many years. In Australia, industry emissions of particulate matter less than 10 microns in size has increased from 530 million kilograms in 2009/2010 to 920 million kilograms in 2013/2014, representing a significant and increasing problem (Australian Government - Department of the Environment, 2014). Issues associated with excess dust emissions include health implications, environmental pollution, material loss, and equipment deterioration due to the adverse operating environment. Worker morale and productivity can also be negatively affected by excess workplace dust, and of course, there is the important need to comply with increasingly stringent regulations primarily from a pollution and health perspective. These issues vary with dust properties and concentration, which is directly related to the quantity of material handled and the control methods implemented. One of the primary control methods implemented today consists of water sprays designed to wet material as a way of limiting dust release, however, the effectiveness of this method is limited and varies from application to application. Many of these systems also suffer from high consumption of valuable clean water. Improved design methods in combination with high energy micro mist nozzles will be presented in this paper as a means of developing much higher efficiency dust control systems with lower rates of water consumption and decreased costs compared to the water spray systems commonly in use today.

In the coal industry, there are two specific operational areas that have been identified as troublesome for the control of dust (among many others); run-of-mine (ROM) dump hoppers and stockpile stackers. These operations can generate relatively large quantities of dust in conditions, which can be described as challenging at best. The outdoor nature of these operations means that they are particularly susceptible to wind disturbances and the high drop heights that are present result in the development of fast moving and "dense" dust clouds. To achieve a notable improvement in the control of dust in these areas it is necessary that new technologies be developed, and improved design techniques established. Research conducted at the University of Wollongong has identified two enabling technologies that can

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result in this improvement; the application of high energy micro mist sprays and the use of computer-aided engineering (CAE) techniques, specifically Computational Fluid Dynamics (CFD).

OPTIMISING DUST CAPTURE EFFICIENCY

To optimise the efficiency of a dust control/suppression system the key influencing variables must first be identified. Generally, the first component selected in the design of a dust suppression system is the nozzle type which is selected based on Droplet Size Distribution (DSD), spray penetration, mist density, spray angle, and droplet velocity. These are all a function of spray nozzle design and input conditions (e.g. water pressure). The aspect of a nozzle's performance most important to its effectiveness at capturing dust is droplet size. The reason for this is related to Stokes' law, which describes the frictional force or drag forces that are exerted on a spherical object moving in a viscous fluid. As both a droplet and a dust particle travel through the air they will impart a force on the air which will alter their motion and effect their interactions with each other. Figure 1 depicts this interaction. If a very small object is travelling towards a larger object, the fluid flowing around the large object will impart a force on the small object causing it to become entrained in the disturbed air and travel around the object rather than impacting with it. The greater the difference in size the more pronounced this effect will be and as such the less likely it is that impact will occur. Based on this explanation it can be concluded that to maximise the potential of dust capture by water droplet it is most important to have droplets of similar size to the dust particles being captured. Furthermore, as well as having droplets of similar size, it is also necessary to have droplet concentration or mist density greater than the concentrations of dust in the air such that all the dust can be captured.

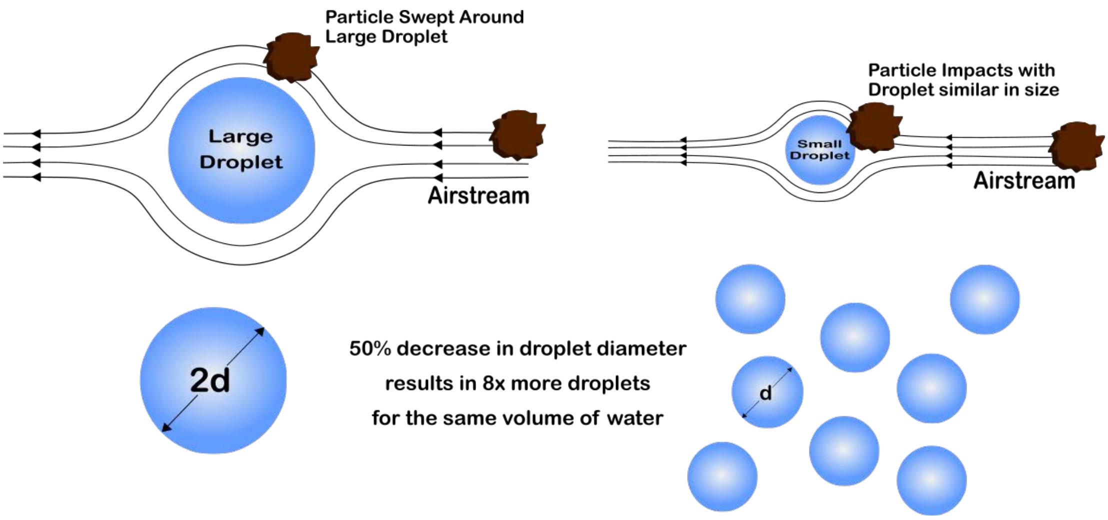

Figure 1: Particle-droplet interaction

Given this knowledge, it is now possible to analyse the performance of systems currently in use. There are two forms of spraying systems that are commonly used for dust suppression; systems using water only sprays generally at relatively low pressures producing a coarse droplet spray, or systems using air atomising nozzles producing a very fine low-velocity mist. These systems have their own advantages and limitations dependent on the conditions. Most water only spraying systems produce a relatively low concentration of coarse droplets with an aerodynamic diameter in the range of 200-600 microns (Yao-she, Gao-xian, Jun-wei, & Xiao-bo, 2007). The coarse droplets result in a spray that can handle crosswinds without too much deviation and can span large distances, however, the large droplet size and low concentration do not result in good capture efficiencies as fine dust particles easily escape through the space between the droplets resulting in minimal dust-to-droplet impact. On the other hand, air atomised sprays produce very fine droplets of a relatively high concentration, which are extremely effective at capturing fine dust particles (d_{50}< 50 microns). These air atomisers, however, do not deal well with significant air flow or highly concentrated dust clouds and are easily blown away in these conditions resulting in poor dust capture performance. Furthermore, air atomisers also add air into the dust-air problem that is already present. The issues presented here plague the performance of many systems typically found in coal mines and go some way to explaining the poor performance of many of the systems currently installed in the industry.

To develop more efficient systems a solution must be found that consists of sprays with correctly sized droplets, high droplet concentrations, and with sufficient energy to withstand adverse air flow conditions. These requirements led to the development of high energy micro mist nozzles (EnviroMist). These nozzles operate at pressures ranging typically from 100-300 bar and produce a highly dense and finely atomised spray with high capture effectiveness even in adverse conditions such as high cross winds. The comparison below (Figure 2) shows a standard water only spray versus a high energy micro mist both captured in one ten-thousandth of a second. The first thing to note is the droplet size, the traditional spray produces coarse droplets which are easily visible in the image and the droplet size distribution shows the droplet diameter (DV50) of micro-mist spray being less than one sixth of the coarse droplet spray. These coarse droplets are much larger than the dust particles they aim to capture and as a result they are generally very inefficient. Secondly, the two sprays are vastly different in their droplet concentration although having similar water consumption. This is a function of the decreased droplet size resulting in millions more droplets dramatically increasing the probability of capture. The two sprays shown in Figure 2 have the same water consumption, however, given the improved capture efficiency of these sprays, it has been found that they can be operated at flow rates as much as 50% lower than current systems. This is significant given the importance of sustainable water usage rates; it has been reported that up to 70% of the water supply in the Pilbara is used for mining activities with 50% of this being used for dust suppression purposes (Mills, 2010).

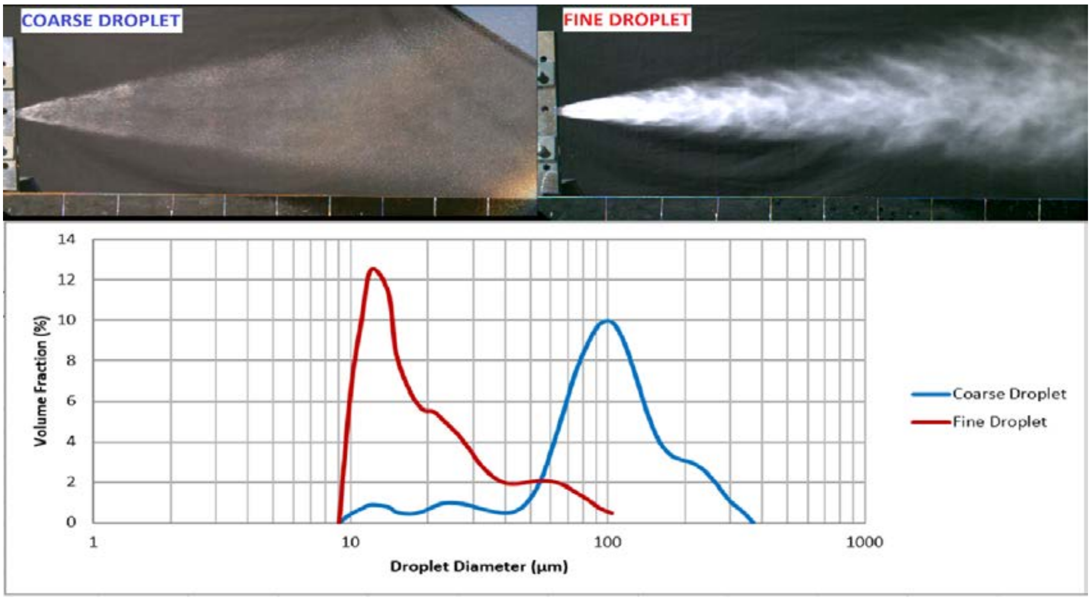

Figure 2: Comparison of coarse-droplet and fine droplet micro-mist sprays

DESIGN METHODOLOGY

The effectiveness of airborne dust suppression systems can be significantly improved by understanding the physics involved as described above and by making basic considerations based on readily available data. Considerations that need to be made are summarised below:

- Environmental factors
- Size of focus area
- Wind velocities
- Water consumption/availability
- Physical barriers
- Hazards (such as machine or equipment movements and flying rock,
- Dust properties, including Particle Size Distribution (PSD)
- Velocity

- Concentration
- Nozzles Selection and Position
- Positioned for maximum coverage, maintenance access, and free of any interference issues that could cause damage
- Nozzle selection for maximum capture efficiency

Nozzle selection and positioning are dependent on both the dust properties and the environmental factors. Nozzles need to be selected so that they produce water droplets of similar size to the dust particles to ensure effective capture (as described earlier) – this is achieved by proper selection of both the nozzle and its operating conditions (higher pressure leads to smaller droplets but increased water consumption for a specific nozzle). The velocity of the mist is also of vital importance and is dictated by the choice of nozzle and the operating parameters; this should be selected based on the area to be covered and the energy of air and dust flows that will be encountered by the mist. The position should be determined based on maximum coverage of the dust-air flow region whilst ensuring the nozzles are safe from damage – this can be easily determined using a 3D-CAD package in combination with mist profile data.

Matching droplet size with dust particle size has been demonstrated in Figure 3 (Wypych, Hastie, Wangchai, & Grima, 2015), allowing optimal capture efficiency of the dust particles by the water droplets.

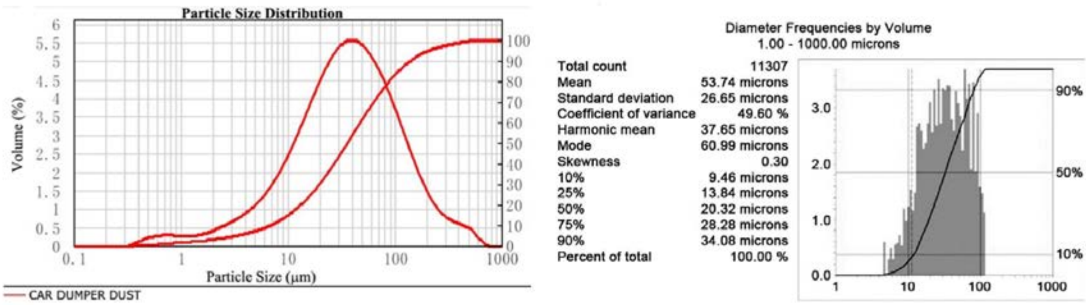

Figure 3: PSD of dust compared with water DSD
(Wypych, Hastie, Wangchai, & Grima, 2015)

Measurement of air and dust flows that occur in the application is also of vital importance, making sure to consider the worst-case scenario and the common case to find an acceptable compromise. This data can be considered as a design variable for selection of an appropriate nozzle and/or the correct operating conditions for a selected nozzle. The effect that dust-air flow in an area has on the mist produced by a specific nozzle can be investigated by using numerical modelling methods, specifically CFD simulations. An investigation and description into the use of CFD for this purpose is presented in the next section. The penetration distance of the mist under varying conditions is the key parameter that should be measured using this technique to ensure that the mist maintains the desired coverage under the required conditions.

Once a nozzle and its operating conditions are selected, the mist should be modelled using 3D-CAD software with a basic model of the site. This allows the nozzle positioning to be determined and more easily visualised ensuring full coverage of the desired area whilst maintaining maintenance access and protection from damage. An example of this is shown in Figure 4, a full coverage high energy spraying system designed for a standard Run-of-Mine (ROM) bin. The system is designed to minimise possible damage from falling rocks or machinery in the area, as well as providing full mist coverage appropriate to the application.

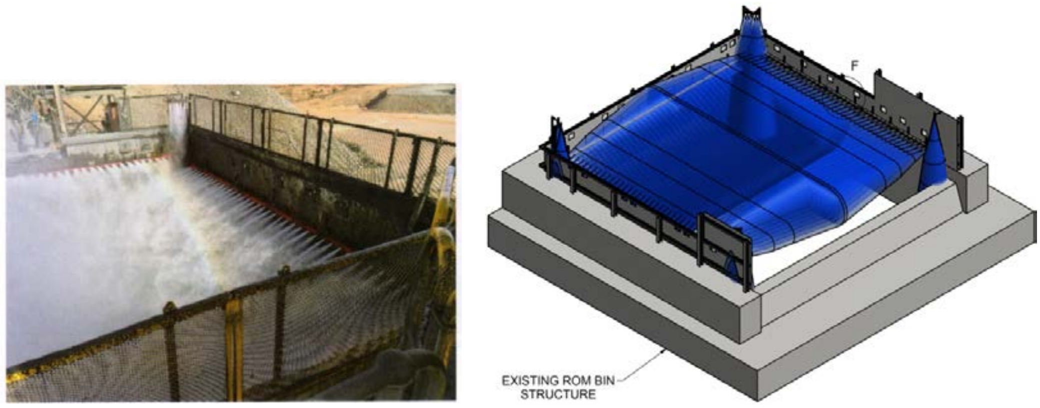

Figure 4: Dust suppression system for ROM bin

NUMERICAL MODELLING

Numerical modelling of the sprays used for dust suppression purposes presents the opportunity to understand the flow dynamics and develop a solution with confidence versus the trial and error based approaches that are commonly used. Research has been completed to develop a validated and best practice approach of using CFD to model sprays under varying conditions. ANSYS Fluent is the primary CFD package that has been used; Fluent provides Volume-of-Fluid (VOF), Eulerian and mixture models as well as a discrete phase model that uses Lagrangian trajectory tracking. There are two methods that are commonly used for spray modelling, Eulerian-Eulerian or Lagrangian-Eulerian. The volume-of-fluid method uses the Eulerian reference frame and is a free surface modelling technique which allows fluid-to-fluid interfaces to be modelled this is important for the modelling of the interaction of droplets with air. The VOF method requires an extremely fine mesh to model the breakup and motion of very small droplets and as such is extremely computationally expensive. The discrete phase model uses Lagrangian trajectory tracking coupled with a continuous Eulerian phase to model droplets not as free surfaces but as discrete particles moving through the air with drag forces applied per the particle properties and specified drag laws. This technique reduces the need for a very fine mesh and simplifies the model significantly, in turn reducing the computational expense.

The coupled Lagrangian trajectory tracking method was chosen for this application primarily due to the reduced computational expense whilst maintaining acceptable accuracy. This model injects discrete particles into the continuous flow field and tracks the particle trajectory by integrating a force balance on each particle per the Lagrangian reference frame. The force balance can be written as;

$$\frac{d\boldsymbol{u_p}}{dt} = \boldsymbol{F_D}\left(\boldsymbol{u} - \boldsymbol{u_p}\right) + \frac{\boldsymbol{g_x}\left(\boldsymbol{\rho_p} - \boldsymbol{\rho}\right)}{\boldsymbol{\rho_p}} + \boldsymbol{F_x}$$

This equates the particle inertia with the forces acting on the particle. Where F_x is the acceleration term, F_D is the drag force, u and u_p are the fluid phase and particle velocities respectively and, ρ and ρ_p are the fluid and particle densities.

Critical to the accuracy of this model is the meshing method and size used. Two mesh types were investigated; a polyhedral cell mesh and a Cartesian cut cell mesh both with refinement close to the nozzle exit. Previous literature modelling of sprinkler sprays found that a grid resolution of 75 mm was the largest that could be used (Husted, 2007) whilst maintaining accuracy. A mesh independence study was conducted for this application and found that the grid resolution should be less than 30 mm in the far field and less than 5 mm near to the nozzle, with minor difference in accuracy between cut cell and polyhedral meshing methods found. The use of the polyhedral cells did, however, produce a 30-40% reduction in mesh size. For this application, the two-equation realisable k-epsilon model (Shih, Liou, Shabbir, Yang, & Zhu, 1995) was chosen due to its improvement over the commonly used standard k-epsilon model and its optimisation for modelling free-stream turbulence which is most relevant to this application. Two-way modelling is used to accurately account for the interaction between the air and droplets, the Stokes-Cunningham drag model is used as it provided the most accurate result for the spray being modelled.

To establish a validated model extensive experimental research on spray dynamics has been undertaken. This includes measurement of velocity, profile and penetration of many of the micro mist nozzles available under varying conditions. This allows for validation of the numerical model primarily in terms of the turbulence and drag models applied such that the flow dynamics correlates well with real world data.

Model Validation

To ensure the accuracy of simulations it is important that the models are validated against experimental data. There are two conditions that are used to validate the models; a single spray operating in static conditions and a single spray operating under a cross-wind. Experimental data is collected using a variety of laser and imaging techniques with droplet/mist velocity and position the key variables being measured. The data which is shown in Figure 5 was collected using Laser Doppler Velocimetry (LDV); this is the droplet velocity along the centreline of the stream in static conditions. The discrete phase mean cell velocity with distance predicted by the simulation model is also shown in Figure 5. It can be seen that the velocity is slightly over predicted by the simulation however it provides a reasonable estimate allowing the prediction of mist velocity and penetration that can significantly improve the nozzle positioning process.

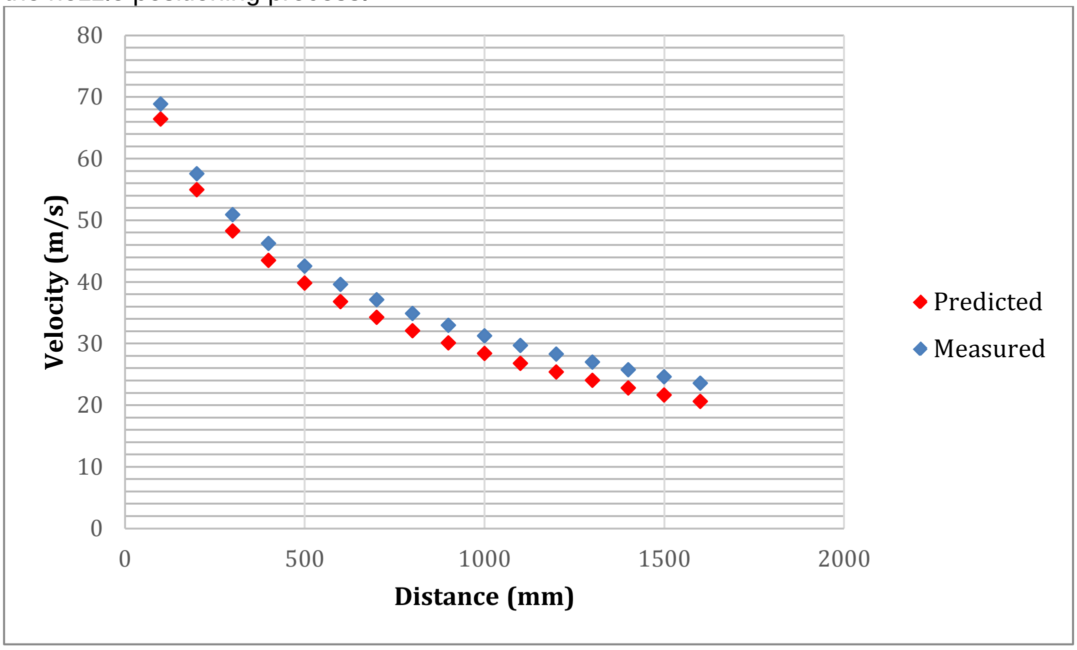

Figure 5: Measured Mean Centreline Velocity of Enviromist Nozzle 1

Figure 6 shows the spray profile produced by the simulation compared with the expected result observed experimentally. Due to the turbulent nature of an atomised spray this profile can be variable, however, acceptable agreement is found between the predicted and experimental data.

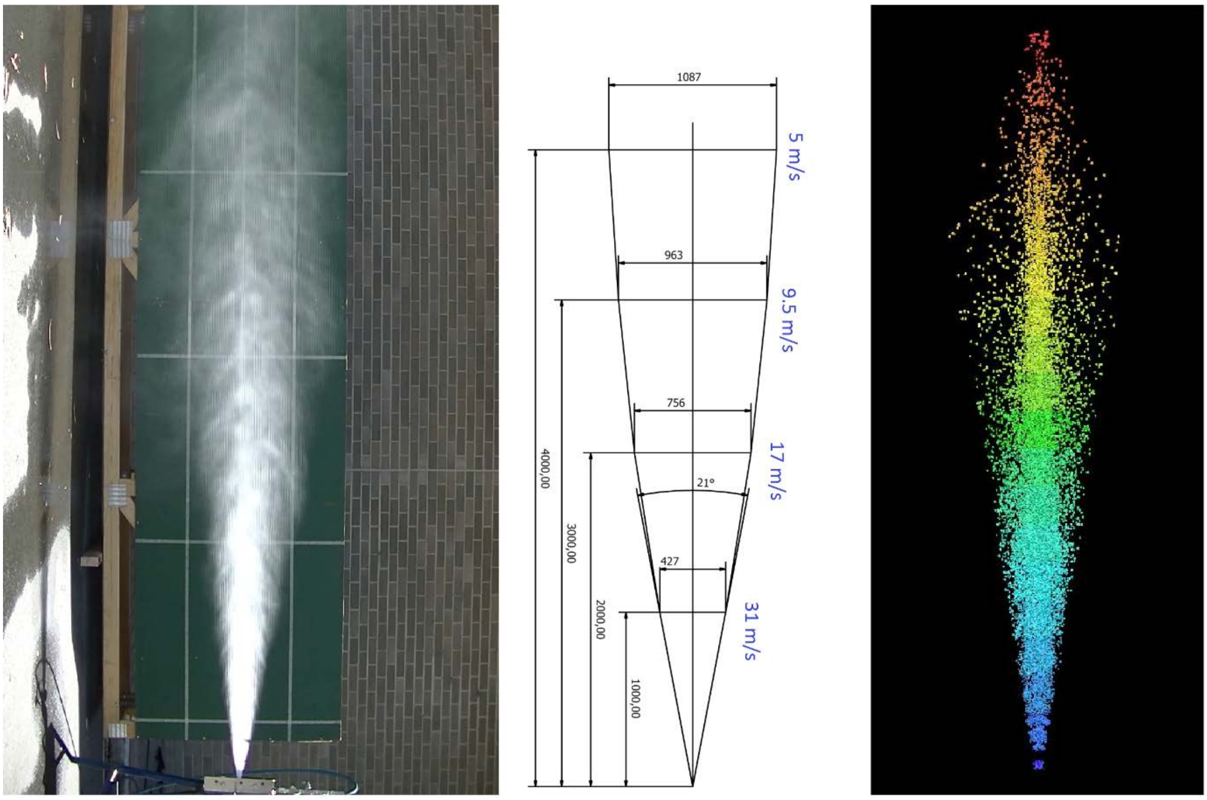

Figure 6: Spray Profile - Experiment *vs* Prediction (Enviromist Nozzle 2)

The second condition that is considered to ensure correlation between experimental and predicted data is the spray geometry under cross-wind conditions. This is achieved through image analysis allowing us to measure the deflected profile of the spray due to the cross-wind. Figure 7 shows the experimental data presented as a measurement of the distance of the spray front from the nozzle exit in the horizontal and vertical directions. Figure 8 shows the predicted mist deflection/predicted profile of one nozzle as simulated using Fluent. There is still some analysis and testing required to get this model to the accuracy required without too much computational expense however the ability to predict this deflection will go a great way to ensuring that nozzles can be correctly selected for conditions associated with any specific application.

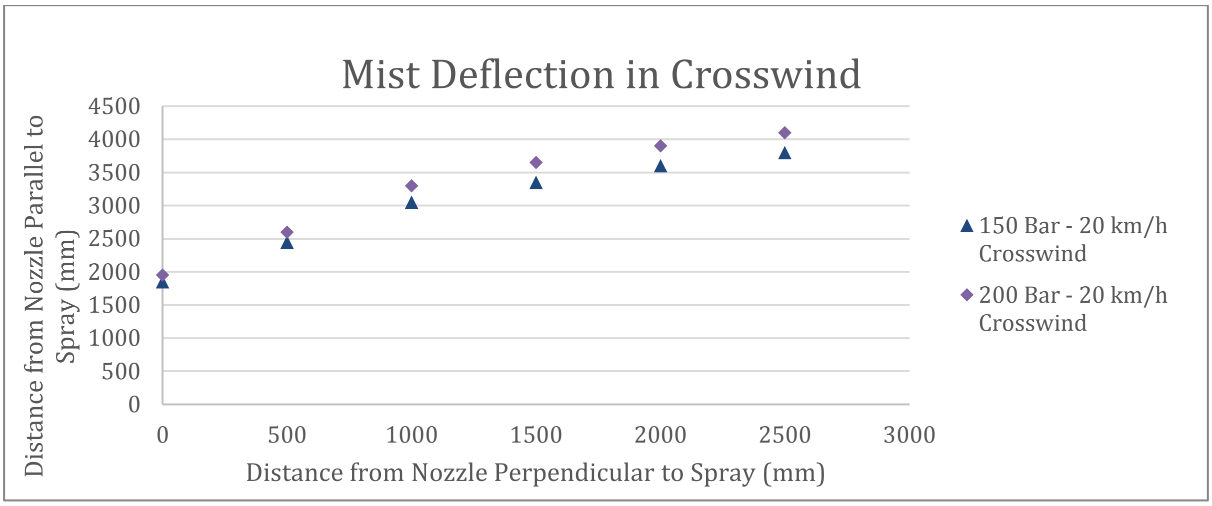

Figure 7: Measured Mist Deflection

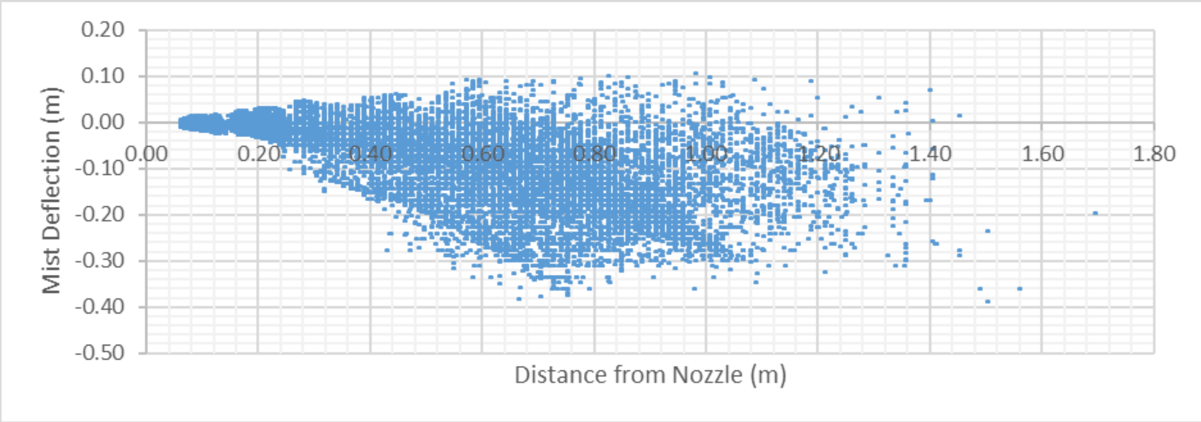

Figure 8: Predicted Mist Deflection

APPLICATIONS

It was identified at the outset of this paper that ROM bins and stockpile stackers are two problematic areas that could benefit from improved dust suppression strategies. It is considered that the application of high energy micro-mist technology in combination with the CAE design approach already described could achieve this. The application of these technologies should result in a reduction in dust emissions, a reduction in water consumption, reduced design effort, and as such an overall reduction in the costs associated with design and operation of the system.

A typical ROM bin using a non-optimised dust suppression system with low-pressure coarse droplet water sprays can consume water at a rate of 1000 L/min with dust capture efficiencies of less than 30% (Courtney and Cheng, 1977). A system utilising micro-mist nozzles, designed with CAD and CFD modelling techniques was installed at a mining operation in late 2015 (modeled in Figure 4). This mine was suffering from significant dust issues with their existing system delivering little to no effective dust capture on the ROM bin. The installed system delivered 100% airborne dust capture and suppression at a water consumption of only 300 L/min, a 700 L/min reduction compared to the original system that was installed.

Other recent applications of this dust suppression technology include: mobile crushing station and stacker (Figure 9); BSL boot end discharge in underground coalmine (Figures 10); grab bucket ship unloading (Figure 12).

Figure 9: Mobile crushing station (before and after dust suppression)

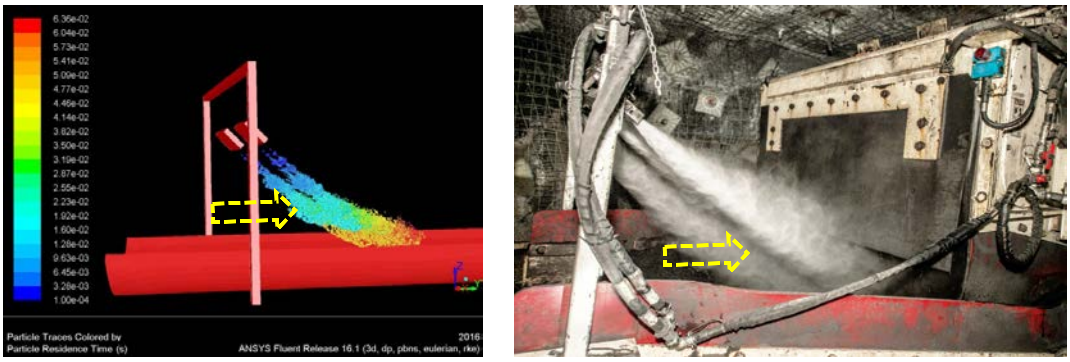

Figure 10: BSL boot end discharge (with new dust suppression)

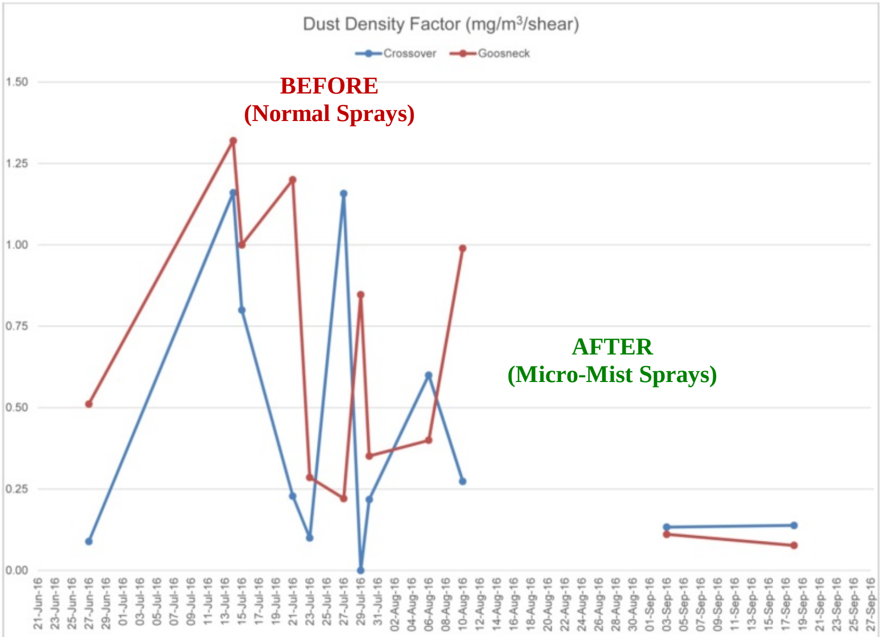

Figure 11: Effectiveness of new dust suppression for BSL

Figure 12: Grab bucket ship unloading (before and after dust suppression)

Stockpile stackers are an area where this technology has not yet been applied. Typically, the control of dust in this scenario is very difficult and generally limited to material wetting on the stacker and surface treatments of the stockpile itself to avoid dust lift-off. The large drop height combined with high winds results in vast amounts of dust being generated. CFD can be used to predict both the air/dust flow as well as the performance of sprays selected for use in this area. Optimisation in this manner can lead to a greater improvement in the initial performance of the system limiting the amount of modification required after installation.

CONCLUSIONS

This paper has outlined the issues associated with excess dust emissions with a specific focus on troublesome areas in the coal industry. High-energy micro-mist nozzles and CFD modelling have been identified as enabling technologies for improving the control and capture of airborne dust. The fundamental principles contributing to effective dust capture by water spraying type systems have to be identified and analysed. Current systems utilising low concentration coarse droplet sprays or low-velocity air atomising sprays do not provide the dust capture performance required in the adverse conditions present in the coal industry. For this reason, a new technology has been presented in the form of high-energy micro-mist nozzles developed by EnviroMist. These nozzles provide high-velocity and high-density fine droplet sprays well suited to the conditions found in mining operations. The use of CFD technology is presented as a means of improving the design and performance prediction of airborne dust suppression systems. A validated model is presented enabling the simulation of sprays in typical conditions allowing prediction the spray dynamics under the expected conditions specific to each individual application. It is expected that this will allow the time taken to design an airborne dust suppression system to be significantly reduced and much higher dust capture efficiencies to be achieved once installed. Finally, some potential future applications are suggested.

ACKNOWLEDGEMENTS

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