Underground Mining Technology 2017 – M Hudyma & Y Potvin (eds)
© 2017 Australian Centre for Geomechanics, Perth, ISBN 978-0-9924810-7-0
doi:10.36487/ACG_rep/1710_08_Witow

Environmental discharge criteria and dispersion estimation for mine ventilation exhaust stacks

W Harris *Hatch Ltd., Canada*

AK Kadiayi *Hatch Ltd., Canada*

K Macdonald *Hatch Ltd., Canada*

D Witow *Hatch Ltd., Canada*

Abstract

Water droplets emitted from mine ventilation discharge points can have a detrimental impact on the environment, and are being recognised as an important source of emission at mine sites. Furthermore, this can lead to poor fan performance, fan wear and reduced fan efficiency, which in turn translates into an increase in overall operating cost.

Droplets are the result of groundwater seepage and/or condensation entrained in the gas stream. Harmful dusts may be incorporated in these droplets. The larger droplets then associated with these dust particles increase their settling velocity and thus dispersion can be substantially reduced.

This paper addresses the issues associated with the characterisation of particle size distribution and illustrates energy losses due to droplets in vertical shafts using pneumatic conveyor calculations. Measuring techniques and abatement technologies are also highlighted.

Keywords: *mining, ventilation, dispersion, droplet, entrainment*

1 Introduction

As the desire and the requirement for environmental stewardship in mining increases, the issue of contamination from exhaust ventilation is receiving increasing attention, including contaminated dust, diesel particulate matter, metals, etc. The presence of water droplets due to groundwater seepage and condensation present both challenges and opportunities for controlling contamination, as will be explored in this paper.

Mine ventilation circuits carry clear airborne contamination from mining, development, and construction activities underground. Dust from blasting, ramp traffic and material handling undergoes some settling and entrainment during passage through mine exhaust airways, with any remaining suspended droplets carried away to surface where release could cause contamination of local soils.

The behaviour of suspended particles and droplets in a mine exhaust system can be understood using the physical principles of a pneumatic conveyor. In the case of vertical airways, pneumatic conveyor calculations can help predict the movement of droplets for a given velocity based on their size and, importantly, the energy lost to friction due to drag which impacts on mine fan duty.

The behaviour of moisture in mine exhaust air is complex. The thermodynamic process of auto-expansion as exhaust travels upward toward the surface cools the air. Depending on starting humidity and dew point, heat transfer from rock surfaces and vertical distance, the air may reach and pass saturation. With new deep mining projects with mine cooling, underground spray chambers will greatly increase the moisture content, making these engineering predictions all the more important.

2 Challenges in characterising environmental discharge

The characterisation and control of environmental discharge from mine exhaust stacks is complicated by the presence of water droplets as well as dust and gaseous contaminants. Few detailed observations of emissions are available for comparison, and conditions can vary greatly by facility, creating unique challenges. Specifically, defining droplet size, quantity and composition can be a significant challenge.

The size distribution of discharged droplets/particles can be difficult to predict. Water entering a shaft airstream could be the result of mine fog, condensation within the shaft, and/or groundwater sources within the shaft, each of which could produce a different characteristic droplet diameter. Observations of mine fog have seen droplets between 1 and 100 µm, with a typical median of 5 to 10 µm (Martikainen & Marks 2007). Droplets entrained from groundwater can be large, with a typical range of 500 to 800 µm, while condensed droplets are smaller, typically less than 50 µm (Derrington 2002). Furthermore, turbulence within the shaft and impaction on the shaft walls may cause droplets to shatter or merge, altering the size distribution. Interaction with surface ducting, exhaust fan, and exhaust stack prior to emission creates further opportunity for droplet size changes.

Refined droplet size analysis is very complex, but some guidance can be provided by simplified analyses. Droplet conveyance is dependent on the relative magnitude of the droplet terminal settling velocity and the shaft airflow velocity: droplets with a settling velocity below the air velocity are carried upwards out of the stack, droplets with a settling velocity greater than the air velocity settle downwards, and droplets with a terminal settling velocity similar to the air velocity can remain suspended in the stack. Thus, the maximum droplet size conveyed by a given shaft can be estimated as that with a terminal settling velocity equal to the stack exit velocity. Moreover, if a mist eliminator is installed at the shaft outlet, the droplet size distribution seen at the stack may be estimated given the expected eliminator performance. Site-specific empirical data may be required for detailed analysis of dust/droplet control.

Predicting the total quantity of water discharged by a stack also presents a challenge. The total volume condensed within the shaft can be estimated for an existing facility by measuring the moisture content and temperature at the shaft inlet. The condensation is then a function of the gas stream thermodynamics over the height of the shaft. For deep shafts, condensation has been observed to produce liquid water at a rate of up to 0.5 L/s (Derrington 2002). The groundwater entrained within the shaft can be estimated by off-line measurements of water discharge at the bottom of the shaft, with previous studies measuring in excess of 5 L/s groundwater infiltration (Derrington 2002). Furthermore, the system water balance can be better defined if surface duct/fan drainage are quantified. Depending on shaft velocity, water could also exit at the bottom of the shaft or drip off the shaft brow and be re-entrained into the exhaust flow.

Water discharge from a mine is certain to contain dissolved and suspended solids. The movement of droplets through an airstream removes dust as in a wet scrubber, by impaction, interception, or diffusion. Also, dust particles can act as nuclei for droplet condensation. The dust content in a droplet will depend on dust control within the mine and the droplet formation mechanism/locations (i.e. condensation or groundwater entrainment). To model the dispersion of droplets discharged from a stack, the density of these droplets must be known. Typically, the dust content within the droplets would not be enough to significantly impact the dispersion analysis, but a correction should be considered for very dusty conditions or where dissolved solids are expected to significantly increase droplet density. However, the inclusion of dust in water droplets greatly impacts the predicted dispersion of dust, as will be discussed later.

3 Capture methods

The practice of capturing water droplets from mine exhaust air has been explored and documented:

- Derrington (2002) explores means of mechanically separating droplets and using dropout chambers.
- Boyko and Smith (2010) establishes a successful application of mist eliminator equipment, including washing spray bars at a uranium exhaust shaft in Saskatchewan.
- Witow and McCall (2010) document the successful application of a dropout chamber at a metal mine exhaust shaft in Ontario.

The obvious benefit of droplet capture is in reduced environmental release of the metals or other forms of contamination associated with the droplets. Secondary benefits include increased reliability of fan systems that are less subject to erosion, corrosion and deposition. In cold environments, capture also leads to improved safety in maintenance due to less ice formation near the fans.

With both demisting and dropout zone droplet capture systems, the most challenging droplets to remove are the smaller fraction. With demisting equipment, the performance of small droplet removal is improved by increasing velocity and decreasing chevron spacing. Increasing velocity by using a lower sectional area increases the energy loss for the unit to the square of the increase in velocity, so power consumption is a concern. More tightly spaced chevrons also increase power consumption and may be more subject to fouling.

The design of a droplet removal system will be subject to the particular sensitivities of each mine site. The control requirements may consider droplets which will be felt on impact with skin (about 60 µm diameter or larger), droplets similar to atmospheric mist (about 100 µm), site-specific environmental limits, or droplet downwind transport distance. Whatever contamination is not captured should be addressed using dispersion, as is explored in the following section.

4 Dispersion methods

Exhaust from a shaft is considered as a point source emission where contaminants released from the shaft are dispersed and diluted with the ambient air. Various meteorological factors such as ambient temperatures, wind speed and direction will dictate the amount of dilution from the shaft to the ground level. Terrain and any obstructions (buildings, equipment, etc.) can impact the flow patterns of the plume from the source to a ground level location. Environmental compliance for dust and gas emissions from point sources are often based on ground level concentration limits at a defined point of impingement (POI). There are several dispersion calculations and modelling tools available to estimate the impact of one or multiple point source emissions on ground level concentrations.

4.1 Overview of dispersion modelling methods

There are several dispersion modelling methods available, but the most appropriate method will depend on the site's regulatory air quality standards for the contaminant of interest and the requirements to prove that these standards are met. As an example, the Ontario Reg. 419/05: Air Pollution – Local Air Quality (Section 6) outlines the approved air dispersion models that can be used to confirm whether the air quality standards are met as follows (Ontario Ministry of the Environment and Climate Change (MOE) 2016, 2017):

- SCREEN3 estimates the impact of single emission sources. It is mainly used for short-term calculations or screening purposes to determine whether a more refined assessment is required using AERMOD.
- AERMOD is a steady state, Gaussian plume model that was developed by the United States Environmental Protection Agency. It can be used to model emissions from multiple sources and source types, e.g. point, volume, area and open pit. It is most applicable for near field impacts (< 50 km) and complex terrain.

- American Society of Heating, Refrigerating and Air Conditioning Engineering (ASHRAE) calculation for building air intake and exhaust design are used for same-structure contamination assessment to ensure rooftop sources do not impact air handling units or intakes in the same building. ASHRAE presents several methods to determine the best exhaust stack and air intake design strategy taking into account downwash and wind recirculation zones. These include (ASHRAE 2015):
    - Geometric method for estimating stack heights that will ensure the lower edge of an exhaust plume is above the air intake and any wind recirculation zones.
    - Exhaust to roof level intake dilution or concentration calculation.
- Regulation 346 methods of calculation/models consisting of (MOE 2005):
    - Scorer and Barrett equation used for POI's up to 5 m horizontally from the point of emission.
    - Virtual Source Dispersion model for stacks/vents less than twice the height above grade.
    - Point Source Dispersion model for stacks/vents greater than twice the height above grade.
- Alternative models that the Ontario Ministry of Environment may specify for a given site/source include:
    - CALPUFF.
    - CAL3QHCR.
    - Shoreline Dispersion Model (SDM).
    - Physical or Wind Tunnel Modelling.
    - AERSCREEN.

These models are generally considered on a case-by-case basis when a more refined assessment is required.

4.2 Droplet dispersion modelling method

Exhaust stacks contain droplets and particulates of various sizes. In the absence of the detailed meteorological and terrain input data required for a refined dispersion analysis (e.g. via AERMOD, CALPUFF) the following section describes how the ASHRAE geometric method mentioned in Section 4.1 was adapted for a desktop evaluation for the dispersion of droplets and particles of varying droplet sizes. As mentioned, this geometric method describes the plume edge to ensure a particular downwind receptor is completely cleared; thus, plume dilution is not directly considered. Applied to stack droplet discharge, this adapted method enables estimation of the maximum droplet size which will clear a defined downwind distance within a typical range of wind conditions. This maximum droplet size can then be used as an input into an emission control strategy.

The desktop method that will now be described has many inherent assumptions and should be considered as a guide for droplet dispersion and control requirements. It is not meant to replace detailed dispersion analysis as required for regulatory compliance. The ASHRAE geometric method on which this droplet analysis is based was developed for short-range transport within the vicinity of the exhaust stack. The application of this geometric method to longer-range transport may be overly conservative; a typical Gaussian dispersion profile significantly diverges from the conical ASHRAE geometric dispersion profile at greater downwind distances. Furthermore, the assumptions inherent to typical dispersion analyses also apply to this adjusted method, including:

- Constant emission rate.
- Constant wind speed, wind direction and atmospheric stability.
- Plume mass transfer is primarily the result of bulk air movement in the downwind direction.
- Plume composition/characteristics remain static over transport.

The assumption of static plume characteristics over transport is of particular concern for application to droplets. This method inherently ignores any droplet condensation or evaporation as droplets travel downwind of the stack. During cold periods, droplets may grow with condensation, thus increasing droplet mass and therefore settling velocity, potentially decreasing downwind transport. By contrast, warm periods may see droplets reducing in mass during transport resulting in greater downwind travel.

4.2.1 Terminal velocity of droplets

In order to adapt the ASHRAE method, the terminal velocity of varying droplet sizes was considered. The terminal settling velocity of a droplet can be estimated assuming a spherical particle dependent on particle properties, atmospheric properties, and flow regime, as per Perry and Green (2008). Particle drag and, as a result, settling velocity are related to the flow regime of the fluid. Stokes' law can be used to estimate the terminal settling velocity in low Reynold's number flow regimes and is considered a conservative estimate of terminal velocity in other regimes. Regime-specific drag coefficients can be applied to terminal velocity estimation for improved accuracy. Regime-corrected terminal velocities for a range of water droplet diameters are provided in Figure 1. Note that this analysis ignores the added mass from suspended and dissolved solids within the droplets.

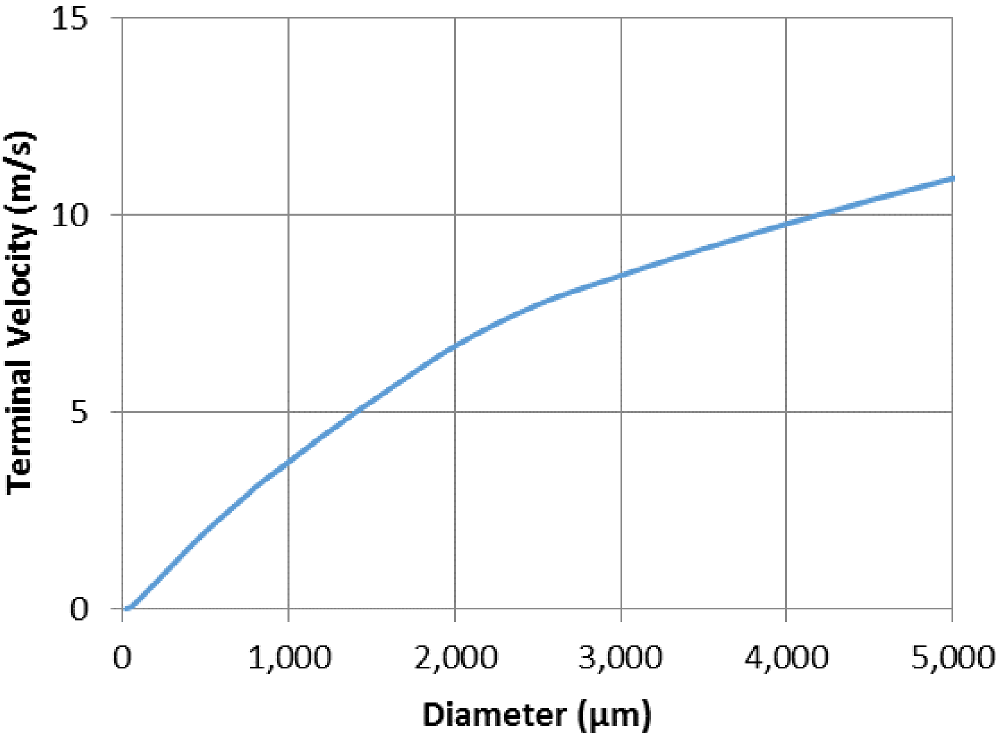

Figure 1 Water droplet terminal velocity

4.2.2 Adapted ASHRAE geometric method

The application of the ASHRAE geometric method is for a point source emission (stack/vent) on a building roof. The recommended stack height to clear a receptor/POI includes estimation of plume rise, downwash, and recirculation zones around intakes/buildings. The key assumption of this method is that the plume spreads in the vertical direction (both up and down) with a constant 5:1 (H:V) slope (ASHRAE 2015). The method has been adapted to increase this slope to account for the impact of gravity acting on the droplets. As shown in Figure 2, the exhaust plume edge is assumed to expand at a constant gradient as it travels downwind.

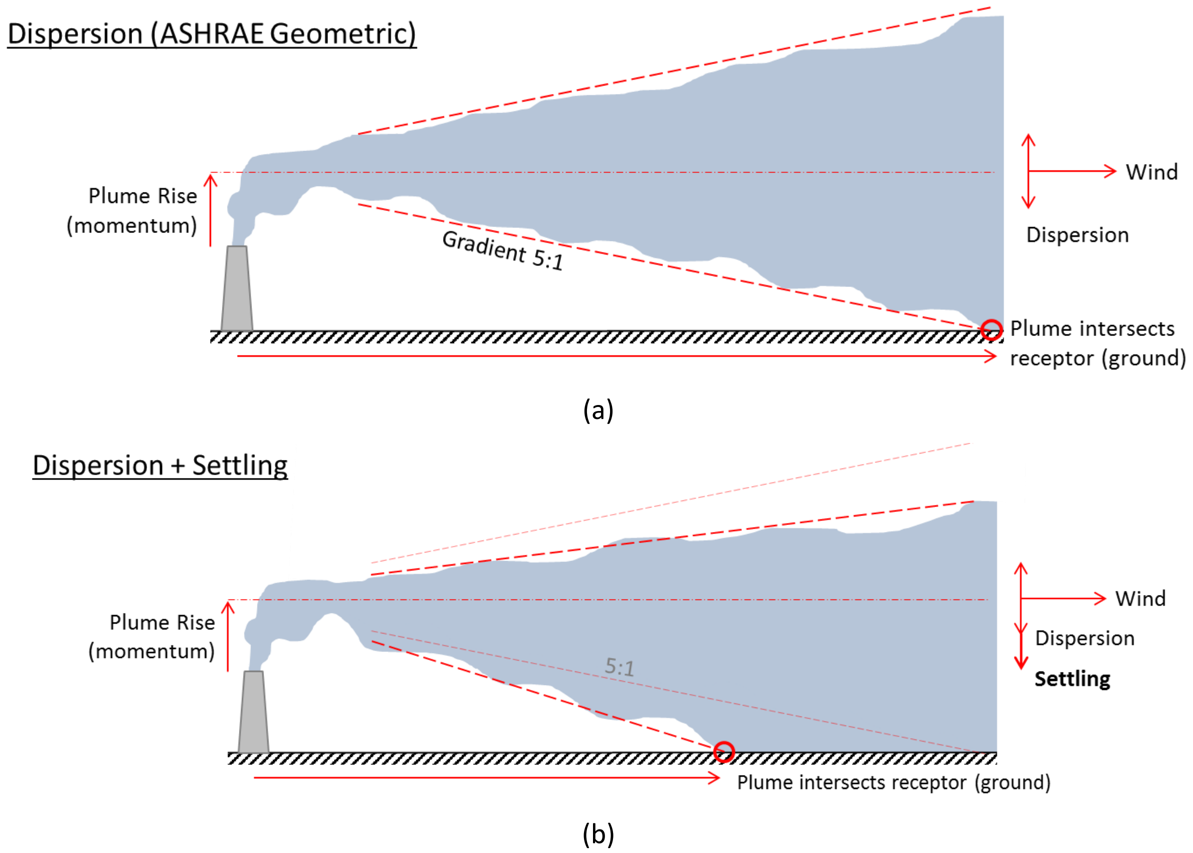

Figure 2 **Dispersion conceptual model (a) excluding; and, (b) including droplet settling**

The gradient used in the ASHRAE geometric method is described in Equation 1 along with the adjusted gradient to incorporate settling. The steeper gradient reduces the horizontal distance downwind from the stack that the lower edge of the plume is predicted to intersect the receptor, considered as ground level in this analysis. Any receptor closer to the stack than this interception distance is considered to be fully cleared by the plume.

$$Gradient_{Disp.} = \frac{H}{V} = \frac{U_S}{U_S/_5} = 5 \quad ; \quad Gradient_{Disp.+Sett.} = \frac{H}{V} = \frac{U_S}{U_S/_5 + V_t} \tag{1}$$

where:

H = horizontal component of transport (m).

V = vertical component of transport (m).

U_S = wind speed at the top of stack in the horizontal direction (m/s).

V_t = terminal settling velocity of droplet (m/s).

Thus, when only dispersion is considered, the downwind transport distance of the plume edge is simply a factor of five greater than the effective stack height (i.e. the height corrected for plume rise and downwash). When the impact of droplet/particle settling is considered, the horizontal component of transport remains the same (wind speed = U_S), but the vertical component of transport includes both dispersion (U_S/5) and settling (V_t). Therefore, as the particle mass approaches zero, the downwind transport distance approaches that of dispersion alone; whereas, as the particle mass increases, the increased terminal velocity leads to decreased transport distance. This adjusted gradient inherently assumes that all droplets leaving the stack are constantly falling at their terminal velocity relative to the surrounding plume air.

Both the dispersion and dispersion + settling models are impacted by plume rise and downwash. While downwash decreases the effective stack height at lower wind speeds, momentum plume rise increases the effective stack height at lower wind speeds, and typically plume rise is the controlling factor for the effective stack height of mine exhaust stacks. Thus, low wind speeds typically correspond to farther downwind transport. However, settling exhibits the opposite impact with wind speed. For a given particle with a constant settling velocity, a lower wind speed will lead to a smaller horizontal/vertical gradient; thus, droplets will impact the ground closer to the stack. For a distribution of droplets, larger droplets settle more quickly and therefore closer to the stack at a constant wind speed. The contrasting relationships of wind speed with effective stack height and the dispersion + settling gradient create a non-linear system.

A sample analysis can be used to illustrate the interaction of wind speed and droplet size for an assumed typical mine exhaust stack: 10 m height, 3 m diameter, 18 m/s exit velocity, and uncapped. Pure spherical water droplets are considered for this example, ignoring any dust content. Figure 3 shows the distance downwind from the stack where the edge of the plume is predicted to first intersect the ground (receptor).

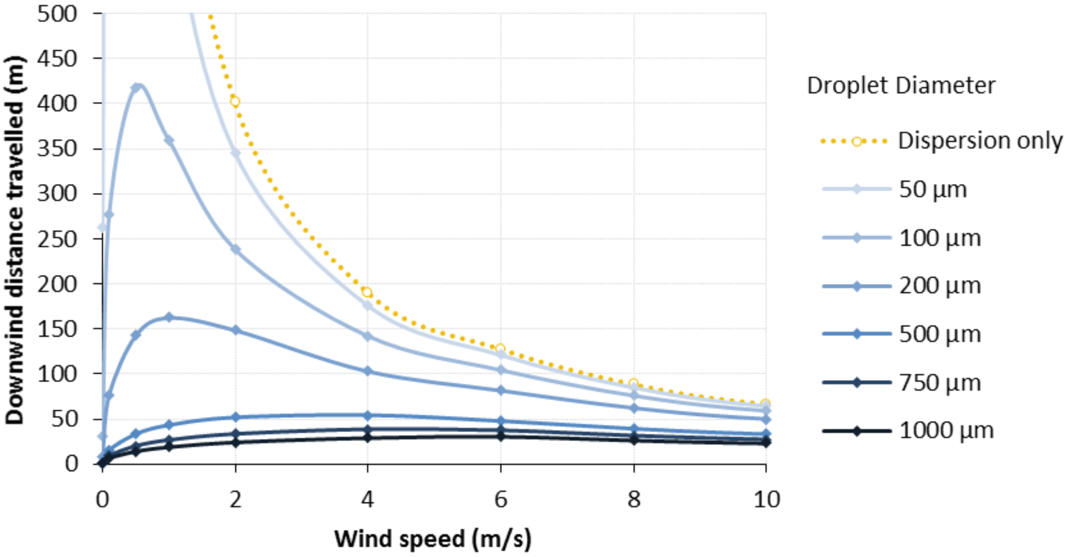

Figure 3 Downwind transport distance by droplet size for a sample stack

The counteracting impacts of wind speed are illustrated in Figure 3. When settling is ignored (i.e. dispersion only as shown in yellow), a logarithmic decline in travel distance with increased wind is observed. The transport gradient is constant as shown in Equation 1 and only the effective stack height changes with wind speed. However, settling droplets show a peak wind speed, below which settling dominates the transport, decreasing the transport distance and above which dispersion dominates, decreasing the transport distance. For example, the 100 µm diameter droplet, which has an estimated 0.1 m/s settling velocity, shows a maximum horizontal transport distance of 420 m at a wind speed of around 0.5 m/s. The wind speed associated with this inflection point varies by particle size, increasing to about 4 to 6 m/s for the larger 750 and 1,000 µm droplets considered.

The distinct curve for settling droplets shown in Figure 3 introduces a significant difficulty in exhaust control measures. For non-settling plumes, the stack can be designed such that a certain downwind distance is exceeded for any reasonable wind speed. In contrast, emitted droplets will settle in the vicinity of the stack during calm wind conditions regardless of stack design. Droplet/particle removal is therefore of upmost importance.

Figure 3 demonstrates another significant challenge; that droplet size has a significant impact on the dispersion distance. At a wind speed of 2 m/s a typical mist droplet of 100 µm will travel about 250 m downwind, while droplets less than 50 µm in diameter may travel farther than 350 m. This is an important consideration in dust control and regulatory approvals where the dispersion of a respirable dust particle with a diameter below 10 µm will change significantly if incorporated into a larger water droplet, changing the area impacted by respirable dust.

5 Modelling of droplets in vertical shafts

Water blanketing, often caused by airborne droplets produced via condensation or groundwater entrainment, can result in an increase in mine shaft resistance. In most cases, recommendations are made to simply avoid air velocities lying between 7 and 12 m/s, which typically includes the critical velocity for water conveyance (McPherson 2012). While this approach provides a safety margin, little research has been published on the effects of water blanketing and their implications on shaft resistance. This section provides a brief discussion on the application of a pneumatic conveying approach to appreciate the effects of water blanketing.

Pneumatic conveying of solid particles has been studied in depth; it has been applied successfully to the conveyance of a wide range of solid particles over a variety of applications. In general, particles can be transported in dilute suspension or in dense phase. In dilute suspension, large volumes of air at high velocities are required to fully suspend solid particles while in dense phase transport, particles are not fully suspended, resulting in higher interactions between particles. Design and applications for both modes of transport are extensively covered in most books on particle technology and pneumatic conveying as well as various sources in the literature, including Klinzing et al. (2011) and Rhodes (2008).

In vertical pneumatic conveying, the delineation between dilute and dense phases is defined by the choking velocity defined as the lowest velocity at which particles can remain suspended in the airstream for a particular solids feed rate. Particles are fully suspended when the airstream velocity is higher than the choking velocity.

As demonstrated in calculations to follow, a dilute phase transport model can be assumed to define the movement of water droplets in an upcast shaft. Some of the key assumptions made to achieve this include:

- Coalescence of water droplets is not considered.
- Water droplets behave as solid particles.
- Fluid–particle interaction for a single particle is assumed.
- Terminal settling velocity of water droplets is assumed to be equal to the slip between water droplets and the airstream (Rhodes 2008).

Using the method presented by Rhodes (2008), an analysis was conducted to find out how much pressure increase would result from condensate in a postulated ventilation raise. For one Canadian mine with a potential exhausting capacity of 183 m^3/s, a condensation rate of 0.82 L/s was calculated and taken into account at the bottom of the ventilation raise. The high level of condensation was due to the presence of a mine air cooling plant condenser spray cooler. An assumed range of droplet sizes was selected based on sizes often quoted for various abatement technologies. Other parameters for the mine and the resulting pressure increase due to condensed water for the given range of droplet sizes are presented in Table 1 and Figure 4.

Table 1 Ventilation raise parameters

Raise depth	950 m	Barometric pressure	112 kPa
Raise diameter	0 to 300 m depth: 3.36 m	Air velocity	14.9 and 17.4 m/s
	300 to 950 m: 3.96 m	Condensed water	820 ml/s
Total raise resistance	0.0713 $N.s^2/m^8$	Temperature	34.3°C
Flow rate at 3.36 and 3.96 m	172 and 183 m^3/s	Relative humidity	100%

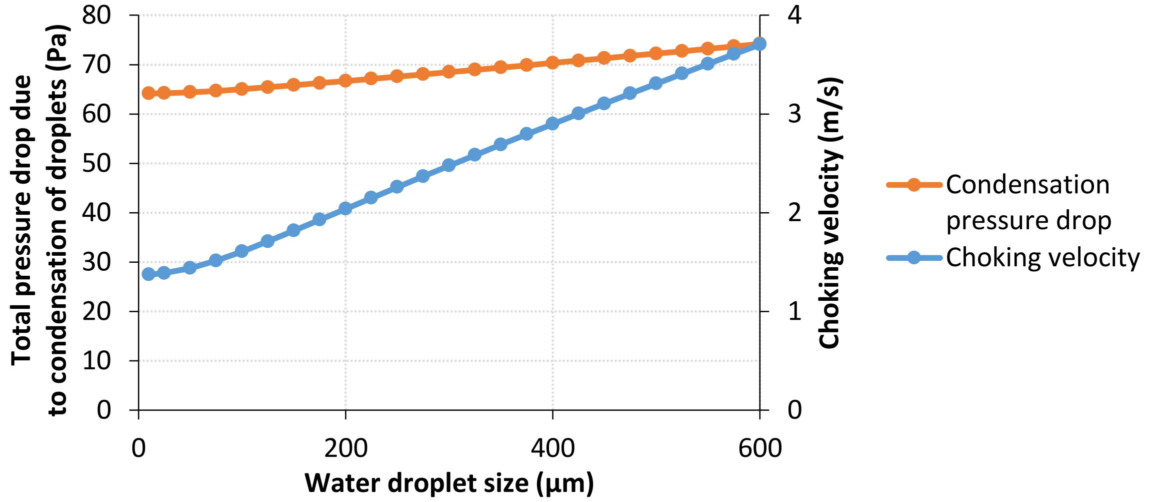

Figure 4 Relationship between droplet size and pressure drop, fixed mass flow and velocity

The pressure drop is shown to be only weakly related to the droplet size. The analysis would be applicable for groundwater seepage, assuming the source is near the bottom of the shaft.

The vertical pneumatic conveying concept can be similarly applied to understand the behaviour of water blanketing across a wide range of velocities and estimate the associated increase in power consumption. Considering the smallest and largest droplet sizes, as well as a shaft diameter of 3.81 m and conditions as defined in Table 1, the power increase for a fixed flow of 5,820 mL/s at the bottom of the shaft is estimated as shown in Figure 5. Power is strictly considered as a function of pressure drop and flow rate in the shaft, which were determined based on the method outlined by Rhodes (2008).

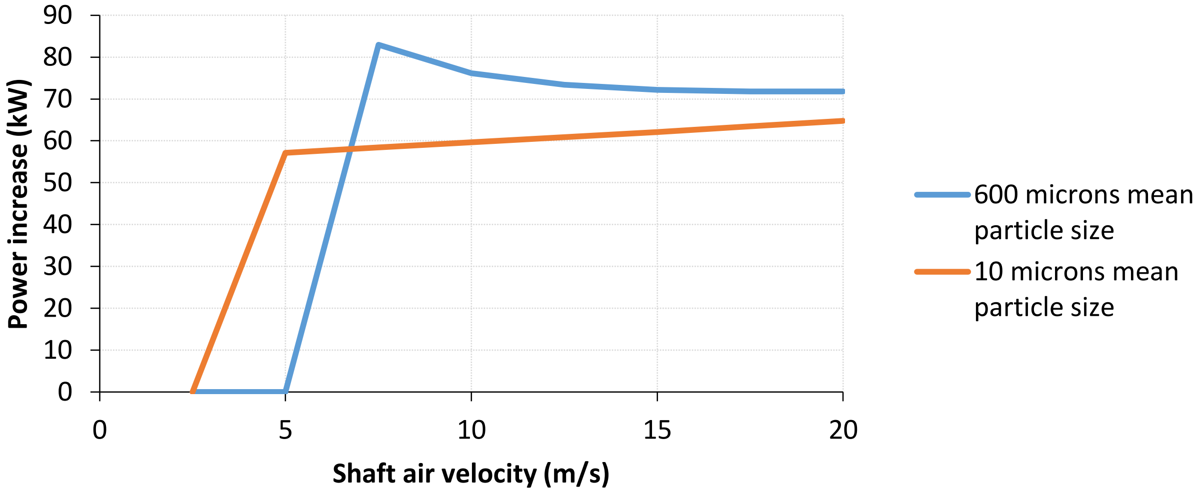

Figure 5 Power increase resulting from a change in shaft air velocity

This rather crude, yet efficient, simplification provides some degree of appreciation for the surge in power which might occur at a critical velocity for a known mean particle size. Particles are assumed to fall when the air velocity is lower than the choking velocity in this case; therefore, there is no increase in power at lower air velocities. In reality, the demand on pressure will rise substantially if particles need to be conveyed at velocities lower than the choking velocity.

If dilute phase conveyance is assumed to occur below the choking velocity and above the terminal settling velocity of the particles, we can explore the implications of particles travelling close to terminal velocities. This is illustrated in Figure 6 over a range of mean particle sizes.

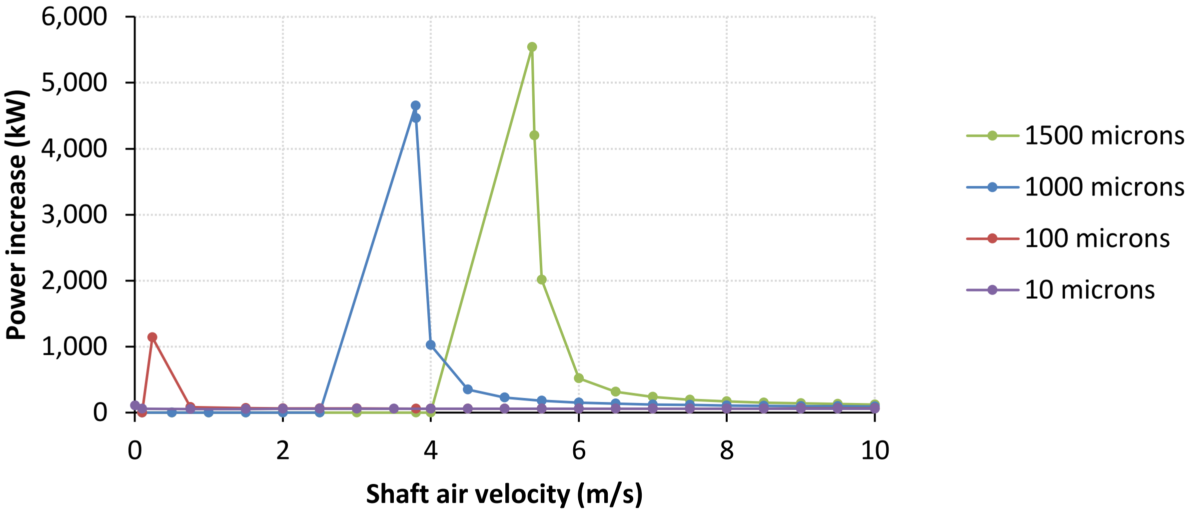

Figure 6 **Power increase at varying shaft air velocities, fixed water flow**

A substantial increase in power can be observed when the shaft air velocity approaches the terminal settling velocity of the particle.

This analysis does not demonstrate the water blanketing effect because a range of particle sizes are assumed to exist at all parts of the airstream and thus there is no single air speed where most or all droplets are continuously suspended. One key simplification and possible explanation is that this analysis does not consider any interactions of droplets in the airways. Because droplets will have different relative velocities based on their size, it is likely that collisions will happen between. Interactions with the rock walls are also likely. These effects may change the droplet size distribution. The shift in distribution will depend on initial conditions and will differ by site. For a typical mixture of larger droplets and small condensed mist, i.e. a droplet distribution with a large standard deviation, it is possible that droplet–droplet and droplet–wall interactions could drive the distribution towards a relatively consistent stable diameter. That is, if droplets are undergoing a process where they collide and coalesce until they reach an unstable size when they break up and repeat the process, a normalisation of droplet size may occur. Such circumstances could exacerbate the water blanket effect if droplets converge on a size which would not be effectively removed from shaft.

6 Conclusion

The prediction of the size of airborne contamination in mine exhaust air is a key challenge in designing containment and dispersion systems. The physical interactions between droplets, shaft walls, and fan equipment will impact droplet size in a way that may not be possible to predict without empirical data.

Removal of droplets and associated contamination from the exhaust airstream is possible through physical separation equipment such as demisters or dropout chambers, but these methods are more effective on the larger size fraction.

ASHRAE methods can be used to quickly understand the dispersion performance for a given site, across a range of droplet sizes and stack exit conditions. Other methods may be prescribed by the regulator in certain jurisdictions for preparing permitting submittals.

Pneumatic conveyor calculations are a useful tool when applied to mine exhaust shafts, as they allow the quantification of pressure and energy losses due to entrained droplets.

Real achievement in environmental protection is possible in the area of mine exhaust air contamination. The analytical tools available to projects can provide useful and reliable means of predicting contamination, but like many areas of engineering, are subject to accurate data inputs, in this case, droplet size distribution.

References

American Society of Heating, Refrigerating and Air Conditioning Engineering (ASHRAE) 2015, 'Building intake and exhaust design', *ASHRAE Handbook: HVAC Applications*, ASHRAE, Atlanta.

Boyko, K & Smith, T 2010, 'Innovative use of a mist eliminator in mine ventilation', *Proceedings of the 3rd International Conference on Uranium*.

Derrington, AS 2002, 'Control of water discharge from mine ventilation shafts', *Proceedings of the Underground Operators Conference*, The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 317–326.

Klinzing, GE, Rizk, F, Marcus, R & Leung, LS 2011, *Pneumatic Conveying of Solids: A Theoretical and Practical Approach*, Springer Science & Business Media.

Martikainen, AL & Marks, J 2007, 'Fogging in mines: the role of visibility, unfamiliar fog removal methods, and future research ideas', *Journal of the Mine Ventilation Society of South Africa*, Q2.

McPherson, MJ 2012, *Subsurface Ventilation and Environmental Engineering*, Springer Science & Business Media.

Ontario Ministry of the Environment and Climate Change (MOE) 2005, *R.R.O. 1990 Regulation 346: General – Air*, Ontario Ministry of the Environment and Climate Change, Ontario.

Ontario Ministry of the Environment and Climate Change (MOE) 2016, *Ontario Regulation 419/05: Air Pollution – Local Air Quality,* Ontario Ministry of the Environment and Climate Change, Ontario.

Ontario Ministry of the Environment and Climate Change (MOE) 2017, *Air Dispersion Modelling Guideline for Ontario (Guideline A-11)*, version 3.0, Ontario Ministry of the Environment and Climate Change, Ontario.

Perry, RH & Green, DW 2008, *Perry's Chemical Engineers' Handbook*, 8th edn, McGraw-Hill, New York.

Rhodes, MJ 2008, *Introduction to Particle Technology*, John Wiley & Sons Ltd, Chichester.

Witow, DR & McCall, J 2010, 'Engineering innovation at Xstrata's Nickel Rim South surface exhaust fans', in S Hardcastle & DL McKinnon (eds), *Proceedings of the 13th United States/North American Mine Ventilation Symposium*, MIRARCO Mining Innovation, Sudbury, pp. 545–552.