CHAPTER 20. THE AERODYNAMICS, SOURCES AND CONTROL OF AIRBORNE DUST

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20.1. INTRODUCTION

The physical characteristics of aerosols have been subjected to intensive study for the free surface atmosphere. This is an important area in meteorology and investigations of the behaviour of contaminant plumes in the atmosphere. Somewhat less attention has been paid to the aerodynamic characteristics of dust when the carrying airstream is confined within the boundaries of ducts or tunnels.

The first main section in this chapter outlines the several phenomena that govern the manner in which airborne dust is transported through the branches of a ventilation network and the deposition of dust particles on the roof, floor and sides of mine airways.

A prerequisite to the successful control of airborne dust in a mine is an understanding of the potential sources of the dust. These are discussed in the second main part of the chapter. While some sources are obvious such as a power loader or tunneling machine, others are less so including the crushing of immediate roof strata by modern powered roof supports. The final section outlines the methods of dust control in mining operations. These include prevention of the formation of dust, suppression and removal of dust particles from the air, isolating personnel from concentrations of dust and the diluting effects of airflow. The latter was introduced in Section 9.3.3.

Readers who are interested only in the practical aspects of the topic are advised to concentrate on Sections 20.3.2 to 20.4.1 and 20.4.2.2 to 20.4.4.

20.2. THE AERODYNAMIC BEHAVIOUR OF DUST PARTICLES

The very large size range of dust particles that exist in the ventilation system of an active mine results in a variety of differing phenomena influencing the behaviour of the particles. The smallest particles act almost as a gas and react to molecular forces while the larger particles are influenced primarily by inertial and gravitational effects. In this section we shall consider the influence of gravitational settlement, molecular diffusion, turbulent or eddy diffusion, coagulation, impingement, re-entrainment and computer simulations.

20.2.1. Gravitational settlement

The rate at which a particle falls through air under the action of gravity depends not only upon the size and density of the particle but also its shape. In Section 19.2.1., the concept of an equivalent geometric diameter based on projected area was introduced. This is the diameter of a sphere that has the same projected area as the actual particle.

The majority of analyses in this subject assume that each particle is a homogeneous sphere. In the study of particle aerodynamics this has given rise to further alternative definitions of equivalent diameter including:

- **Stokes’ diameter**: the diameter of a sphere that has same density as the actual particle and falls through air at the same rate

- **aerodynamic diameter**: the diameter of a sphere of density 1 g/cm³ that falls through air at the same rate as the actual particle.

Despite these additional definitions, the geometric diameter remains the one that is most commonly used in practice.
20.2.1.1. Stokes' Law and terminal velocities. When any body is suspended in a fluid, at least two forces act upon it (Figure 20.1). One is the weight of the body within the prevailing gravitational field. The volume of a sphere of diameter $d$ is $\frac{1}{6} \pi d^3$ m$^3$. If this has a density of $\rho_s$ (kg/m$^3$) then its weight becomes

$$\frac{1}{6} \rho_s \pi d^3 g \quad \text{N} \quad (20.1)$$

where $g$ = gravitational acceleration (m/s$^2$)

However, the sphere displaces its own volume of fluid and will experience an opposing upthrust equal to the weight of fluid displaced, i.e.

$$\frac{1}{6} \rho_a \pi d^3 g \quad \text{N} \quad (20.2)$$

where $\rho_a$ = density of the fluid (kg/m$^3$)

The net force causing downward movement is the combination of the two:

$$\frac{1}{6} \pi d^3 g (\rho_s - \rho_a) \quad \text{N} \quad (20.3)$$

If the particle is moving relative to the fluid then it will experience a further resistance or drag because of viscous shear and conversion of some of its kinetic energy into turbulent eddies within the fluid. A general expression for drag was given in Section 5.4.6.2. as

$$\text{Drag} = C_D A_b \rho_a \frac{u^2}{2} \quad \text{N} \quad (20.4)$$

where $C_D$ = coefficient of drag (dimensionless)

$u$ = relative velocity between the particle and the fluid, m/s

and $A_b$ = projected area ($= \pi d^2/4$), m$^2$

Many investigators have investigated relationships between $C_D$ and Reynolds' Number, Re, for fully submerged bodies (e.g. Prandtl 1923). In the case of spheres, the diameter is used as the characteristic length in the calculation of Reynolds' Number. For the particular case of laminar flow around a particle, Sir George G. Stokes (1819-1903), the Cambridge physicist, showed that

$$C_D = \frac{24}{Re} \quad (20.5)$$
Now, as \( \text{Re} = \frac{\rho_s ud}{\mu_a} \), where \( \mu_s \) = dynamic viscosity of the fluid (Ns/m²),

\[ C_D = \frac{24 \mu_s}{\rho_a ud} \]

Substituting for \( A_b \) and \( C_D \), equation (20.4) gives

\[ \text{Drag} = \frac{24 \mu_s \pi d^2}{\rho_a ud} \frac{u^2}{2} = 3 \pi \mu_a d u \quad \text{N} \quad (20.6) \]

As the particle accelerates downwards, its velocity, \( u \), increases until the drag equals the downward force quantified in equation (20.3)

\[ \frac{1}{6} \pi d^3 g (\rho_s - \rho_a) = 3 \pi \mu_a d u \quad \text{N} \quad (20.7) \]

At that point of dynamic equilibrium, the velocity of fall becomes constant and is renamed the terminal velocity, \( u_t \). Equation (20.7) may now be rearranged as

\[ u_t = \frac{d^2 g (\rho_s - \rho_a)}{18 \mu_a} \quad \text{m/s} \quad (20.8) \]

Equations (20.6 to 20.8) have all been referred to as Stokes’ Law.

Stokes’ Law applies with good accuracy to particles that are above the respirable range (5 microns). Smaller particles become sensitive to slippage and molecular forces. Stokes’ Law is based on the assumption of laminar flow. If the terminal velocity is sufficiently high to cause the onset of a turbulent wake then the transfer of kinetic energy from the particle to the fluid (inertial effects) can no longer be ignored. The upper limit of Stokes’ Law occurs at a Reynolds Number, \( \text{Re} \), of about 0.1 which, for many mineral particles falling at their terminal velocity through air, is equivalent to geometric diameters of approximately 20 microns.

For larger particles at their terminal velocity, \( u_t \), we may balance equations (20.3) and 20.4):

\[ \frac{1}{6} \pi d^3 g (\rho_s - \rho_a) = C_D \frac{\pi d^2}{4} \rho_a \frac{u_t^2}{2} \]

giving

\[ u_t = \sqrt[3]{\frac{4}{3} \frac{d g (\rho_s - \rho_a)}{C_D \rho_a}} \quad \text{m/s} \quad (20.9) \]

For dust particles in air, \( \rho_s >> \rho_a \) and the term \( (\rho_s - \rho_a) \) is usually truncated to \( \rho_s \). Flagan and Seinfeld (1988) suggest the approximations for coefficients of drag, \( C_D \) given in Table 20.1.
Reynolds’ No., Re & $C_D$

<table>
<thead>
<tr>
<th>Re</th>
<th>$C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 0.1$</td>
<td>$\frac{24}{Re}$ (Stokes’ Law)</td>
</tr>
<tr>
<td>$0.1 &lt; Re &lt; 2$</td>
<td>$\frac{24}{Re} \left[ 1 + \frac{3}{16} Re + \frac{9}{160} Re^2 \ln(2Re) \right]$</td>
</tr>
<tr>
<td>$2 &lt; Re &lt; 500$</td>
<td>$\frac{24}{Re} \left[ 1 + 0.15 Re^{0.687} \right]$</td>
</tr>
<tr>
<td>$500 &lt; Re &lt; (2 \times 10^5)$</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Table 20.1 Approximations for coefficients of drag for spherical particles (after Flagan and Senfeld, 1988)

20.2.1.2. Slip flow

Stokes’ Law applies to dust particles that are large in comparison to the mean free path of the gas molecules. Hence, those particles see the gas as a continuum. As the particle size approaches the mean free path of the gas molecules this no longer holds. Two effects are then observable; first the jerky dislocations caused by molecular bombardment, known as Brownian motion and discussed in Section 20.2.2., and secondly, the drag force reduces as the small particle becomes more able to move or "slip" through intermolecular voids.

In order to quantify the very small distances now being considered, let us recall that the mean free path of a gas molecule is defined as the average distance it moves between collisions with other gas molecules. Although air is a mixture of gases, it is convenient to treat it as a single gas of equivalent molecular weight 28.966 and gas constant 287.04 J/kgK.

From the kinetic theory of gases it can be shown that the mean free path, $\lambda$, is given by

$$\lambda = \frac{\mu}{0.499 P (\frac{8}{\pi R T})^{\frac{3}{2}}} \text{ m} \quad (20.10)$$

where $\mu$ = dynamic viscosity of fluid (Ns/m²)

$P$ = pressure (N/m²)

$R$ = gas constant (J/kgK)

and $T$ = absolute temperature (K)

For air at $P = 100$ kPa, $T = 293$ K (20 °C), $R = 287.04$ J/kgK and $\mu_a = 17.9 \times 10^{-6}$ Ns/m² (Section 2.3.3.),

$$\lambda = \frac{17.9 \times 10^{-6}}{0.499 \times 10^5 \left(\frac{8}{\pi (287.04 \times 293)}\right)^{\frac{3}{2}}} = 6.52 \times 10^{-8} \text{ m or 0.0652 microns.}$$

When particle diameters fall below 5 microns, the effect of slippage becomes significant. In order to extend the applicability of Stokes’ Law, a correction factor, $C_c$, can be introduced to reduce the calculated value of drag. Thus, for small particles equation (20.6) is corrected to

$$\text{Drag} = \frac{3 \pi \mu_a d u}{C_c} \text{ N} \quad (20.11)$$
A number of relationships between $C_c$ and $d$ have been suggested (e.g. Allen and Raabe, 1982), based mainly on a series of classical experiments on liquid aerosols carried out by Millikan between 1909 and 1923. Values of the slip correction factor for air at 25 °C and 101 kPa are given in Table 20.2.

<table>
<thead>
<tr>
<th>$d$ (microns)</th>
<th>0.01</th>
<th>0.05</th>
<th>0.1</th>
<th>0.5</th>
<th>1.0</th>
<th>5.0</th>
<th>10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_c$</td>
<td>22.7</td>
<td>5.06</td>
<td>2.91</td>
<td>1.337</td>
<td>1.168</td>
<td>1.034</td>
<td>1.017</td>
</tr>
</tbody>
</table>

Table 20.2. Slip correction factor for dust particles in air (after Flagan and Seinfeld, 1988).

The equation $C_c = \frac{9.56 \times 10^{-8}}{d^{1.045}} + 0.99$, with $d$ expressed in metres, gives $C_c$ within an accuracy of 2 percent.

Incorporating the slip correction factor into Stokes' Law for terminal velocity, equation (20.8) gives a relationship that can now be extended down to a particle size of 0.01 microns:

$$u_t = \frac{d^2 g (\rho_s - \rho_a) C_c}{18 \mu_a} \text{ m/s} \quad (20.12)$$

Figure 20.2 gives a graphical representation of this equation for particles of varying diameter and density falling through air of temperature 20°C. The curvature of the lines on this log-log plot is due to the effects of slippage.

Example
Determine the terminal velocities and time taken for particles of geometric equivalent diameter 0.1, 1, 10 and 100 microns to fall a distance of 2m through air of density $\rho_a = 1.1$ kg/m$^3$ and dynamic viscosity, $\mu_a = 18 \times 10^{-6}$ Ns/m$^2$. The density of the dust material is 2000 kg/m$^3$.

Solution
The terminal velocities for the 0.1, 1, and 10 micron particles can be estimated from the $\rho_s = 2000$ kg/m$^3$ curve on Figure 20.2. For more precise values the slip corrected Stokes' equation (20.12) gives

$$u_t = \frac{d^2 g (\rho_s - \rho_a) C_c}{18 \mu_a}$$

$$= \frac{9.81(2000 - 1.1) d^2 C_c}{18 \times 18 \times 10^{-6}} = 6.052 \times 10^7 d^2 C_c$$

Applying this relationship to each of the given particle diameters and reading corresponding values of $C_c$ from Table 20.2 (remembering to multiply microns by $10^{-6}$ to convert diameters to metres) gives

<table>
<thead>
<tr>
<th>$d$ (microns)</th>
<th>0.1</th>
<th>1</th>
<th>10</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slip correction, $C_c$</td>
<td>2.91</td>
<td>1.168</td>
<td>1.017</td>
<td>1</td>
</tr>
<tr>
<td>$u_t$ (m/s) calculated</td>
<td>$1.761 \times 10^{-6}$</td>
<td>$7.069 \times 10^{-5}$</td>
<td>$6.155 \times 10^{-3}$</td>
<td>out of range</td>
</tr>
<tr>
<td>$u_t$ (m/s) estimated from Figure 20.2</td>
<td>$1.75 \times 10^{-6}$</td>
<td>$7.1 \times 10^{-5}$</td>
<td>$6.0 \times 10^{-3}$</td>
<td>out of range</td>
</tr>
</tbody>
</table>
Figure 20.2  Slip corrected terminal velocities and Brownian displacements of dust particles falling through still air of viscosity $17.9 \times 10^{-6}$ Ns/m$^2$ (20°C). Based on equations (20.12) and (20.17 with barometric pressure of 100kPa and $g = 9.81$ m/s$^2$.}
These terminal velocities for the 0.1, 1.0 and 10 micron particles are acceptable as the diameters fall into the range of applicability of the slip-corrected Stokes’ equation. The 100 micron particle, however, is well above the 20 micron limit for laminar flow and we must revert to the more general equation (20.9). This requires a value of coefficient of drag, $C_D$. Table 20.1 would allow us to calculate $C_D$ if we knew the Reynolds’ Number. Unfortunately, that depends upon the terminal velocity which we are trying to find. The problem can be solved iteratively, starting from the approximation $u_t = 0.605 \text{ m/s}$ given by the Stokes’ equation, (20.8).

$$\text{Re} = \frac{\rho_a d u_t}{\mu_a} = \frac{1.1 \times 100 \times 10^{-6} \times u_t}{18 \times 10^{-6}} = 6.111 u_t$$

$$= 6.111 \times 0.605 = 3.7$$  \hspace{1cm} (20.13)

Table 20.1 gives the appropriate expression for coefficient of drag as

$$C_D = \frac{24}{\text{Re}} \left(1 + 0.15 \text{Re}^{0.687}\right) = \frac{24}{3.7} \left(1 + 0.15 \times 3.7^{0.687}\right) = 8.882$$  \hspace{1cm} (20.14)

Equation (20.9) now gives an improved value of $u_t$

$$u_t = \frac{4 d g (\rho_s - \rho_a)}{3 C_D \rho_a} = \frac{4 \times 100 \times 10^{-6} \times 9.81 (2000 - 1.1)}{3 1.1 \times C_D}$$

$$= \frac{1.5417}{\sqrt{C_D}} = 1.5417 \text{ m/s}$$  \hspace{1cm} (20.15)

Equations (20.13, 20.14 and 20.15) can readily be entered into a programmable calculator or spreadsheet software for iterative solution. The values of the variables over eight iterations are as follows.

<table>
<thead>
<tr>
<th>$u_t$ (m/s)</th>
<th>Re</th>
<th>$C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.605</td>
<td>3.7</td>
<td>8.88</td>
</tr>
<tr>
<td>0.517</td>
<td>3.16</td>
<td>10.10</td>
</tr>
<tr>
<td>0.485</td>
<td>2.96</td>
<td>10.66</td>
</tr>
<tr>
<td>0.472</td>
<td>2.89</td>
<td>10.90</td>
</tr>
<tr>
<td>0.467</td>
<td>2.85</td>
<td>11.00</td>
</tr>
<tr>
<td>0.465</td>
<td>2.84</td>
<td>11.05</td>
</tr>
<tr>
<td>0.464</td>
<td>2.84</td>
<td>11.06</td>
</tr>
<tr>
<td>0.463</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The procedure converges to $u_t = 0.463 \text{ m/s}$

The time taken for each of the particles to fall through 2 m can now be determined as $t = 2 / u_t$.

<table>
<thead>
<tr>
<th>diameter (microns)</th>
<th>$u_t$ (m/s)</th>
<th>$t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>$1.761 \times 10^6$</td>
<td>315 hours</td>
</tr>
<tr>
<td>1.0</td>
<td>$7.069 \times 10^5$</td>
<td>7.9 hours</td>
</tr>
<tr>
<td>10</td>
<td>$6.155 \times 10^3$</td>
<td>5.41 minutes</td>
</tr>
<tr>
<td>100</td>
<td>0.463</td>
<td>4.32 seconds</td>
</tr>
</tbody>
</table>

It is clear from this example that little gravitational settlement of respirable dust (< 5 microns) can be expected within the retention times of ventilated areas underground. Coupled with the effects of Brownian motion, submicron particles can be considered to remain in permanent suspension. Indeed, Figure 20.2 indicates that for the 0.1 micron particle Brownian displacement is the dominant effect.
20.2.2 Brownian motion

For very small particles, the bombardment by fluid molecules is no longer balanced on all sides. The result is that the particles undergo random and jerky displacements. This is known as Brownian motion and can be seen under an optical microscope.

20.2.2.1. Brownian displacements

As Brownian movements are random, it is necessary to analyze their effect statistically on a complete population of particles. If we consider a vertical plane in still air of uniform dust concentration and with only Brownian motion causing horizontal movement of the particles, then the average displacement of particles moving through the plane in one direction (+ x ) will be equal to the average displacement of particles in the opposite direction (- x ). Hence, the net displacement is zero - not a very useful result. However, if we square the displacements (positive or negative) then the sum is always a positive number. We can then quantify Brownian motion in terms of mean-square displacement, \( \langle x \rangle^2 \)

A relationship for mean-square displacement was first derived by Einstein in 1905\(^1\) (see, also, Seinfeld, 1986) and has been verified by numerous observers:

\[
\langle x \rangle^2 = 2 \frac{MR}{A} T \frac{C_c}{3 \pi \mu d} t \quad \text{m}^2
\]  

(20.16)

where

- \( M \) = molecular weight of gas
- \( R \) = gas constant (J/kgK)
- \( A \) = Avagadro's constant (6022 x 10\(^{23}\) molecules in each kg-mole)
- \( \mu \) = gas viscosity (Pa.s)
- \( t \) = time over which the displacement takes place (s)
- \( C_c \) = collision frequency

(The ratio \( \frac{R_u}{A} = \frac{8314}{6022 \times 10^{23}} = 1.381 \times 10^{-23} \text{ J molecule K}^{-1} \) is known as Boltzmann's constant.)

For air at 20°C (T = 293 K), the viscosity is 17.9 x 10\(^{-6}\) Ns/m\(^2\). Equation (20.16) can then be simplified to

\[
\langle x \rangle^2 = \frac{2 \times 1.381 \times 10^{-23} \times 293 \times C_c t}{3 \pi \times 17.9 \times 10^{-6} d}
\]
or

\[
\langle x \rangle = 6.925 \times 10^{-9} \sqrt{\frac{C_c t}{d}} \quad \text{m}
\]  

(20.17)

Using the values of \( C_c \) given in Table 20.2 and \( C_c = 1 \) for \( d > 10 \) microns, equation (20.17) has been superimposed on Figure 20.2 with \( t \) set at 1 second. This allows the Brownian displacement to be compared with the terminal velocity curves. Inspection of the Figure indicates that at some point, as particle diameter decreases, Brownian displacement becomes predominant. This occurs within the range 0.2 to 0.6 microns, dependent upon the density of the material. At all lower diameters gravitational settlement is effectively nullified.

\(^1\) Historical note: In 1905 Albert Einstein completed his doctoral thesis. It described his studies into the existence and behaviour of atoms and molecules. He rapidly applied this work to explain the phenomenon of Brownian motion. Later that same year he published his groundbreaking Theory of Special Relativity.
20.2.2.2. Brownian diffusivity

A consequence of random Brownian displacements is that migration of particles will occur from regions of higher to lower dust concentrations. We can describe the process as a form of diffusion and obeying Fick's Law:

\[ N_b = D_b \frac{dc}{dx} \]  \hspace{1cm} (20.18)

where

- \( N_b \) is the flux of particles through an area of 1 m\(^2\) in one second [particles/(m\(^2\) s)]
- \( c \) is the concentration (particles/m\(^3\))
- \( x \) is distance (m) in the direction considered
- \( D_b \) is a coefficient known as the Brownian diffusivity (m\(^2\)/s).

Let us now attempt to find a relationship that will allow us to quantify the Brownian diffusivity. Consider the 1 metre cube shown on Figure 20.3. It contains \( c \) particles, i.e. a concentration of \( c \) particles/m\(^3\). In time \( \Delta t \), a net number of those particles, \( \Delta c \), will diffuse across a 1 m\(^2\) plane by Brownian dislocations and as a consequence of the concentration gradient \( dc/dx \).

Let us take the average Brownian dislocation, \( x \), to be the distance through which the particles move in time \( \Delta t \). Hence, their average velocity in the \( x \) direction will be \( x/\Delta t \). Furthermore, the flux across the 1 m\(^2\) plane will be the number of particles involved multiplied by their average velocity, i.e.

\[ N_b = \frac{\Delta c}{\Delta t} \frac{x}{m^2 s} \]  \hspace{1cm} (20.19)

Combining equations (20.18) and (20.19) gives

\[ \frac{dx}{dc} = D_b \frac{dc}{dx} \]

Now, over the very small distance of a Brownian dislocation, \( x (= \bar{x}) \), we can state that \( \Delta c = dc \) and \( \Delta t = dt \), giving \( x \frac{dx}{dt} = D_b \frac{dc}{dx} \).

Integrating both sides between corresponding boundary limits

\[ \frac{x^2}{2} = D_b \frac{dc}{dx} \]  \hspace{1cm} (20.20)

As we chose the distance \( x \) to be the average Brownian dislocation, \( \bar{x} \), we can combine with equation (20.16) to give
(\bar{x})^2 = 2D_b t = \frac{2MRT}{A} \frac{C_c}{3\pi \mu d} t \quad m^2 \quad (20.21)

from which

\[ D_b = \frac{MRT}{A} \frac{C_c}{3\pi \mu d} \quad m^2/s \quad (20.22) \]

Again, for air at 20 °C, inserting the values

\[ MR/A = 1.381 \times 10^{-23} \text{ J/(molecule K)}, \]
\[ T = 293 \text{ K} \]
\[ \mu = 17.9 \times 10^{-6} \text{ Ns/m}^2 \]

and gives

\[ D_b = 2.398 \times 10^{-17} \frac{C_c}{d} \quad m^2/s \quad (20.23) \]

Note, also, from equation (20.20) that the mean dislocation is related to the Brownian coefficient of diffusion

\[ \bar{x} = \sqrt{2D_b t} \quad m \quad (20.24) \]

20.2.3. Eddy diffusion

The previous two sections have considered the effects of gravity and molecular bombardment on dust particles. In ventilated areas, a larger influence is exerted on dust particles by the turbulent nature of the airflow. The transport of dust particles by eddies can also be described by a diffusion equation

\[ \varepsilon = \frac{dc}{dx} \quad \text{particles/m}^2 \text{s} \quad (20.25) \]

where

\[ \varepsilon = \text{eddy diffusivity (m}^2/\text{s)} \]

and

\[ N_e = \text{flux of particles through an area of 1 m}^2 \text{ in one second (particles/m}^2 \text{s)} \]

by eddy diffusion.

The total rate of diffusion by both Brownian action and eddies is given by combining equations (20.18) and 20.25). Then

\[ N = N_b + N_e = (D_b + \varepsilon) \frac{dc}{dx} \quad \text{particles/m}^2 \text{s} \quad (20.26) \]

[A glance back at equations (A15.2) and (A15.5) reveals the analogy with diffusion for both heat and momentum.]

The flux of particles passing from the turbulent core of an airflow through the buffer boundary layer to the laminar sublayer is of particular interest as these are particles that have a high probability of being deposited on the solid surfaces. Gravitational settlement will, of course, add to such deposition on floors or other upward facing surfaces. Eddy action can impart sufficient inertia to a dust particle to carry it into the laminar sublayer. Within the sublayer there are no such eddies. Hence only Brownian bombardment can superimpose further transverse forces. Ignoring any effects of re-entrainment, Brownian dislocations at the surface and away from the surface will be zero. Hence there will be a Brownian concentration gradient towards the surface. Coupled with the initial transverse inertia, this will tend to produce deposition of particles that enter the laminar
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sublayer. As may be expected, this phenomenon is influenced by the same factors that affect the boundary layers of fluid flow through rough ducts, i.e. fluid density, viscosity and velocity (Reynolds' Number) as well as the roughness of the surface.

The average size of eddies grows from zero at the edge of the laminar sublayer to a maximum within the turbulent core and, hence, varies with distance, \( y \), from the surface. In order to take the other variables into account, a *dimensionless distance*, \( y^* \), is defined as

\[
y^* = y \frac{u \rho}{2f \mu}
\]

where \( y \) = actual distance from the surface (m), \( u \) = average velocity of fluid (m/s), \( f \) = coefficient of friction for the surface (dimensionless), \( \rho \) = fluid density (kg/m\(^3\)), and \( \mu \) = dynamic viscosity (Ns/m\(^2\)).

Note that \( \mu \rho / y \) has the form of a Reynolds' Number. (The group \( u/2f \) is sometimes referred to as the *friction velocity*.) Values of eddy diffusivity are suggested in Table 20.3.

<table>
<thead>
<tr>
<th>Dimensionless distance from surface</th>
<th>Eddy diffusivity ( \varepsilon ) (m(^2)/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0 &lt; y^* &lt; 5 ) (laminar sublayer)</td>
<td>( 0.001 \frac{\rho}{\mu} y^*_3 )</td>
</tr>
<tr>
<td>( 5 &lt; y^* &lt; 20 ) (buffer layer)</td>
<td>( 0.012 \frac{\rho}{\mu} [y^*_4 - 1.6]^2 )</td>
</tr>
<tr>
<td>( y^* &gt; 20 ) (turbulent core)</td>
<td>( 0.4 \frac{\rho}{\mu} (y^*_5 - 10) )</td>
</tr>
</tbody>
</table>

Table 20.3. Expressions for eddy diffusivity, \( \varepsilon \), as a function of dimensionless distance from a surface, \( y^* \) (after Owen, 1969).

In order to track the combined Brownian and eddy transverse transportation of dust particles across an airway, it is necessary to carry out integrations of equation (20.26) across each of the zones specified in Table 20.3 (Bhaskar and Ramani, 1988). This is accomplished in a manner similar to that used for convective heat transfer in Appendix A15.3.

20.2.4. Other forms of dust transportation

The processes of sedimentation, Brownian and eddy diffusion, coupled with coagulation, are the predominant mechanisms leading to the deposition of dust particles. There are, however, other phenomena that play a secondary role in governing the behaviour of airborne dust.

Many particles gain an electrical charge during formation. The effects of frictional flow as air moves through a duct or airway can also induce electrical charges on dust particles. Even particles that are initially uncharged may gain dipole characteristics due to Van de Waal's forces. The primary effect of *electrostatic forces* is to increase rates of coagulation (Section 20.2.5).
Suppose a dust particle of charge, \( q \), moves through an electrical field of strength \( E \), then it will experience an electrostatic force, \( qE \). This may occur particularly around electrical equipment. At equilibrium velocity, this force is balanced by fluid drag (equation (20.11) for laminar flow around the particle), giving

\[
\frac{3\pi \mu_d d}{C_c} u_e = qE
\]

where \( u_e \) = the electrical migration velocity relative to the air (m/s).

The induction of an electrical charge on dust particles to assist in deposition is utilized in electrostatic precipitators (Section 20.4.2.3.) and in the control of paint or powder sprays. However, the high voltages that are required impose a limit on the use of such devices in underground openings.

**Phoretic effects** refer to phenomena that impart a preferential direction to Brownian motion. **Thermophoresis** is the migration of particles from a hotter to a cooler region of gas and is caused by the enhancement of Brownian displacement at higher temperatures (equation (20.16)). The dust particles are subjected to greater molecular bombardment from the side of higher temperature. The temperature gradient must be considerable to produce a significant effect and the phenomenon has little influence on dust deposition in mine airways. However, it is utilized in instruments such as the thermal precipitator (Section 19.4.2.).

**Photophoresis** occurs when an intense light beam or laser is employed in a dusty atmosphere. The absorption of light by the particle causes an uneven temperature field to exist around that particle. The resulting excitation of nearby gas molecules causes thermophoresis to occur in a direction that depends upon the induced temperature field around the surface of the particle.

An effect that encourages dust deposition on wet surfaces is **diffusiophoresis**. The migration of water vapour molecules away from an evaporating surface will result in a replacing flux of the more massive air molecules towards the surface. The result will be a net Brownian force on dust particles also towards the surface.

### 20.2.5. Coagulation

In any concentration of dust particles, collisions between the particles will occur due to Brownian motion, eddy action or differential sedimentation. Dependent upon the surface properties of any two such particles, they may adhere together to form a larger single particle. As the process continues, some particles will grow to the extent that their terminal velocity becomes significant and they will flocculate out of suspension. This phenomenon of coagulation is influenced by the number and size distribution of the particles (large particles are more likely to be struck by other particles), temperature and pressure of the air (governing Brownian displacements) and electrical charge distributions. The shape of the particles and the presence of adsorbed vapours on their surfaces also affect the probability of their adhering upon collision.

Analysis of coagulation is, again, an exercise in statistics. Consider, first, a concentration of \( n \) particles in \( 1\text{m}^3 \). The average frequency of collisions (\( dn/dt \) particles involved in collisions per \( \text{m}^3 \) per second) clearly depends upon the number of particles in that space. We can write

\[
\frac{dn}{dt} = -an
\]

where \( a \) = the probability of any two particles colliding. (Negative as the number of discrete particles is decreasing with time.)
However, the probability of collision is itself proportional to the number of particles
\[ a = Kn \quad 1/s \quad (20.30) \]
giving
\[ \frac{dn}{dt} = -Kn^2 \quad \frac{\text{particles}}{\text{sm}^3} \quad (20.31) \]

\( K \) is known as the **coagulation coefficient** or **collision frequency function** \( (\text{m}^3/(\text{particles.s})) \).

Equation (20.31) can be integrated readily:

\[ \int \frac{dn}{n^2} = \int -Kdt \]
\[ \frac{1}{n} = Kt + \text{constant} \]

At \( t = 0 \), \( n = n_0 \) = original concentration of particles, giving

\[ \text{constant} = \frac{1}{n_0} \quad \text{so that} \]
\[ \frac{1}{n} = Kt + \frac{1}{n_0} \quad \left[ \frac{\text{particles}}{\text{m}^3} \right]^{-1} \quad (20.31a) \]

i.e. at any given time, \( t \), the particle concentration is given as

\[ n = \frac{n_0}{n_0 K t + 1} \quad \frac{\text{particles}}{\text{m}^3} \quad (20.31b) \]

Values of the coagulation constant can be found for any given dust cloud by plotting the variation of particle concentration with respect to time. For Brownian coagulation of equal sized particles in a continuum, \( K \) is given by

\[ K = \frac{8}{3} \frac{\text{MR}}{A} \frac{T}{T_0} \quad \frac{\text{m}^3}{\text{particles.s}} \quad (\text{Flagan and Seinfeld, 1988}) \quad (20.32) \]

Hence for air at \( 20°C \),
\[ \text{MR} = 8314 \quad \text{J/K kg-mole,} \quad A = 6022 \times 10^{23}, \]
\[ T = 293 \quad \text{K and} \quad \mu_a = 17.9 \times 10^{-6} \quad \text{Ns/m}^2 \]
giving
\[ K = 0.6 \times 10^{-15} \quad \text{m}^3/(\text{particle. s}) \quad (20.33) \]

Ranges of size distribution and the other matters that influence coagulation result in considerable variations being found in observed values of the coagulation coefficient.

There is a further problem that limits the applicability of this analysis; not only has it taken no account of the differing sizes of particles, \( K \) changes as the agglomerates grow larger. A somewhat more sophisticated approach concentrates on one size range at a time and considers the appearance of particles of that size by agglomeration of smaller particles. Additionally, their progression out of the size range as they continue to grow should be taken into account. Let us assume, for the sake of explanation, that diameters are additive. (Actually, we should use particle volume rather than diameter.) Then, for example, particles of size 10 microns can appear by coagulation of smaller particles. If we employ subscripts to denote the size of particles, then
\[ \frac{dn_k}{dt} \text{ (formation)} = \frac{1}{2} \sum_{i=1}^{k-1} K_{ij} n_i n_j \quad \text{particles formed} \quad \text{m}^{-3} \text{s}^{-1} \quad (20.34) \]

where \( K_{ij} \) is the particular coagulation coefficient for colliding particles of size \( i \) and \( j \)
and \( n_k \) is the number of particles of size \( k \) that are formed from the collisions of \( n_i \) particles
(size \( i \)) and an equal number of \( n_j \) particles (size \( j \)).

However, while all of this is going on, particles of size \( k \) are disappearing because further
coagulation causes them to grow out of that size range. This can occur by each particle size \( k \)
agglomerating with another particle of any size. In this case, we count the number of \( k \) size
particles that are disappearing rather than being formed. Hence, we no longer require the factor
of 1/2 and can write:

\[ \frac{dn_k}{dt} \text{ (disappearance)} = - \sum_{m=1}^{\text{max}} K_{km} n_m n_k \quad \text{particles lost} \quad \text{m}^{-3} \text{s}^{-1} \quad (20.35) \]

where \( \text{max} = \text{largest size of particle to be considered relevant to the processes of coagulation} \)

As \( n_k \) has a single value at any given time, \( t \), it can be brought outside the summation sign.

Combining equations (20.34) and 20.35) gives the overall rate of change of concentration of
particle size \( k \):

\[ \frac{dn_k}{dt} = \frac{1}{2} \sum_{i=1}^{k-1} K_{ij} n_i n_j - n_k \sum_{m=1}^{\text{max}} K_{km} n_m \quad \text{particles} \quad \text{m}^{-3} \text{s}^{-1} \quad (20.36) \]

This result was reported by Chung (1981) but attributed to Smoluchowski. Even more complex
analyses have been conducted for liquid aerosols involving not only particle size changes by
coaagulation but also by evaporation. These are of relevance in meteorology and surface
atmospheric pollution.

20.2.6. Impingement and re-entrainment

The phenomena of impingement and re-entrainment become significant only in situations of high
velocity or excessive turbulence such as may occur in and around ventilation shafts or fan drifts.
In such cases, the momentum gained by some dust particles may cause them to be ejected from
the curved streamlines of eddies and impinge on the walls or other solid objects. Deposition by impaction of the particles on the walls can then occur. This is the principle employed in impact dust samplers such as the konimeter (Section 19.4.2.).

Impact deposition in mine airways is counteracted to some degree by re-entrainment in those same conditions of high velocity and turbulence. A particle on any surface and submerged within the laminar sublayer can be made to roll over the surface by viscous drag of the air when a sufficiently high velocity gradient exists across the sublayer. An accelerated rolling action may cause the particle to bounce until it momentarily escapes beyond the sublayer where capture by eddies can re-entrain it into the main airstream. Chaotic turbulence can have the same effect by transient thinning of the sublayer. The phenomena associated with these boundary layer effects are, again, influenced by Reynolds' Number and surface roughness. Re-entrainment can be analyzed by considering the drag and frictional forces on particles on or very close to solid surfaces (Ramani and Bhaskar, 1984).

20.2.7. Computer models of dust transport

The earlier mathematical models developed to describe dust transport in mine airways were empirical in nature (e.g. Hamilton and Walton, 1961). The growing availability of digital computers since the 1960's, combined with a better understanding of aerosol behaviour, led to the development of mathematical models to simulate the behaviour of dust particles in mine ventilation systems (Bhaskar and Ramani, 1988). Such a model may be based on a form of the convective diffusion equation

$$\frac{dc}{dt} = E_x c \frac{d^2 c}{dx^2} - u \frac{dc}{dx} + \text{sources} - \text{sinks}$$

where $c$ = concentration (particles/m$^3$) $t$ = time (s) $x$ = distance along the airway (m) $u$ = air velocity (m/s) and $E_x$ = turbulent dispersion coefficient in the $x$ direction (m$^2$/s)

This can be solved numerically between given boundary limits of time and distance (Bandopadhyay, 1982) to track the temporal variations of dust concentration along a mine airway. The "sinks" term is determined from the relationships given in the preceding subsections and, in particular, the effects of gravitational settlement, Brownian motion, eddy diffusion and coagulation. The "sources" must be defined as a dust production - time curve or histogram that characterizes the make of dust from all significant sources along the length of airway considered.

20.3. THE PRODUCTION OF DUST IN UNDERGROUND OPENINGS

The majority of dust particles in mines are composed of mineral fragments. Oil aerosols may become significant when drilling operations are in progress. Diesel exhaust particulates can also form a measurable fraction of airborne dust in those mines that utilize internal combustion engines. However, in this Section we shall concentrate on the manner and processes through which mineral dusts are formed. Although the primary means of controlling mine dusts are discussed in detail in Section 20.4 we shall introduce some of these, for particular operations, in this Section.

20.3.1. The comminution process

Mineral dusts are formed whenever any rock is broken by impact, abrasion, crushing, cutting, grinding or explosives. For any given material, the energy input required to break the rock is
proportional to the new surface area produced. As dust particles have a large surface area relative to their mass, it follows that any fragmentation process which produces an excessive amount of dust involves an inefficient use of energy. Before discussing specific operations that produce dust, a valuable insight into particles size distribution can be gained from a brief analysis of the comminution process.

Suppose a given brittle material is broken into fragments and the particles classified into a series of size ranges. Commencing with the mass of finest particles and progressively adding on the mass of each next coarser range, a table of cumulative "mass finer than" can be assembled. If this is plotted against particle diameter on a log-log basis (Figure 20.4) then a straight line is obtained for the smaller particles and curving over at larger sizes. The curve of Figure 20.4 follows an equation of the form

$$M = \left\{ 1 - \left[ 1 - \frac{x}{x_o} \right] ^r \right\} ^m \text{ kg} \quad (20.38)$$

where

- $x$ = particle diameter, (m) - we use $x$ here, temporarily, in order not to confuse diameter with the differential operator, $d$
- $x_o$ = diameter of the initial fragment (m)
- $M$ = cumulative mass finer than size $x$ (kg)
- $r$ = a constant that depends upon the particular comminution process and is a characteristic of the material having values in the range 0.5 to 1 and varying only slightly with the method of comminution. (This is known as the Gaudin Meloy Schuhmann equation (Marshall, 1974; Gaudin and Meloy, 1962).)

If the term $\left[ 1 - x/x_o \right] ^r$ is expanded by the binomial theorem, then for $x << x_o$

$$M = r \left[ \frac{x}{x_o} \right] ^m \text{ kg} \quad (20.39)$$

For dust particles, $x$ is certainly very much smaller than $x_o$. Equation (20.39) quantifies the straight line portion of Figure 20.4 and has been shown to hold for particle sizes down to 0.01 microns (National Research Council, 1980).

Let us now try to find a means of determining (i) the mass and (ii) the number of particles in each size range:
(i) mass
Consider the mass, \( dM \), of particles contained within the incremental range \( x \) to \( x + dx \).
Differentiating equation (20.39) gives
\[
dM = \frac{rm}{x^m_o} x^{m-1} dx = C x^{m-1} dx \quad \text{kg}
\]
(20.40)
where \( C \) = constant for that particular material, process and initial size.

Now let us take a finite size range from, say, \( D/10 \) to \( D \) (e.g. 0.5 to 5 microns). Then integrating equation (20.40) between those limits gives the corresponding mass for that range.
\[
M(D/10 \text{ to } D) = \frac{C}{m} \left[ \frac{x^m}{D/10} \right] = \frac{C}{m} D^m \left[ 1 - \frac{1}{10^m} \right]
\]
or
\[
M(D/10 \text{ to } D) = \text{constant} \times D^m \quad (20.41)
\]
As \( m \) is always positive this equation shows that the mass in each size range increases with particle diameter. In practice this means that only a small part of the total rock broken will be produced as dust particles. For coal, values in the range 5 to 9 kg per tonne (0.5 to 0.9 percent) of particles less than 7 microns have been reported (Qin and Ramani, 1989). However, only a tiny fraction of this will become airborne as respirable dust.

(ii) number of particles
Returning to our infinitely small increment of particle size range, \( x \) to \( x + dx \), the volume of each particle is \( \frac{4}{3} \pi x^3 \). If the material is of density, \( \rho \), then the mass of each particle becomes \( \frac{4}{3} \pi \rho x^3 \). For \( dn \) particles in that range, the total mass becomes
\[
\frac{4}{3} \pi \rho x^3 dn = dM = C x^{m-1} dx \quad \text{from equation (20.40)}
\]
giving
\[
dn = C' x^{m-4} dx \quad \text{particles} \quad (20.42)
\]
where \( C' \) = constant for that material, process and initial size.

Integrating over the finite size range \( D/10 \) to \( D \) gives
\[
n(D/10 \text{ to } D) = \frac{C'}{m-3} \left[ \frac{x^{m-3}}{D/10} \right] = \frac{C'}{m-3} D^{m-3} \left[ 1 - \frac{1}{10^{m-3}} \right]
\]
i.e
\[
n(D/10 \text{ to } D) = \frac{\text{constant}}{D^{3-m}} \quad \text{particles} \quad (20.43)
\]
As \( m \) lies in the range 0.5 to 1.0, this shows that the number of particles rises logarithmically as the particle diameter decreases.

Equations (20.41) and (20.43) indicate that in any rock breaking process, the bulk of mass will appear as larger fragments. However, the number of fine dust particles produced may be enormous. Fortunately, most of those particles remain attached to the surfaces of larger fragments. The degree to which dust particles are dispersed into the air would seem to depend upon the nature of the rock as well as the comminution process. For brittle materials, the fragmentation becomes more ‘explosive’ in nature; the resulting surface vibration causes an enhanced dispersion of dust particles into the air. Hence, although comminution of softer materials may generate more dust particles, a greater proportion of those will remain adherent to the surfaces of larger particles and will not become airborne. The production of airborne respirable dust has been reported in the range 0.2 to 3.0 grams per tonne (Qin, 1989; Knight, 1985).
20.3.2. Mechanised mining

Machines that break rock from the solid have the potential to be prolific sources of dust. These include longwall power loaders, continuous miners, roadheaders, tunnelling machines, raise borers and drills. Figure 20.5(a) illustrates a pick point acting against a rock face. Compressive forces induce a zone of pulverized material immediately ahead of the pick point. As the pick moves forward into that zone, the resultant wedging action produces tensile failure along a curved plane - a chip is broken away. The process is repeated continuously as the pick advances. The majority of the pulverized material is abraded onto the surfaces of the rock face and the chip. The amount of dust produced at the tensile failure plane itself may be quite small in homogeneous brittle material and is influenced by the presence of preformed dust in natural cleavage planes. However, the explosive nature of that tensile failure is a major factor in determining the amount of dust that is projected into the air.

A machine that takes a greater depth of cut will require higher torque and may be subject to greater vibration and bit breakage. However, a comparison of Figures 20.5(a) and (b) indicates that more of the broken material will be in the form of chips and, hence, the amount of dust produced in terms of grams per tonne will be reduced. The specific energy (per tonne mined) will also fall. Figure 20.5(c) shows that the greater area of contact given by a blunt pick will create additional dust in the pulverized zone. If such wear causes a significant reduction in the rake angle (Figure 20.5(a)) then the back of the bit will rub against the newly formed face, absorbing additional energy and producing further pulverized rock. Furthermore, as the clearance angle reduces, the chip may not be ejected efficiently but remain in place to be crushed against the unbroken rock. The design of a rock cutting bit is a compromise between the efficiency of cutting (energy absorbed per tonne), wear characteristics and dust production. Considerable diversity of opinion exists on preferred bit geometries for given machines and rock types.

Another factor that influences the proportion of dust which becomes airborne is the speed at which the pick moves. For any given depth of cut, an increased speed results in greater rate of comminution and, hence, dust production. Additionally, movement of the cutter drum causes a higher relative velocity to be induced between the local airstream and the material on the face (or fragments broken from the face). This assists in entrainment of dust particles into the air (Section 20.2.5.). The effect of pick speed on airborne dust is illustrated on Figure 20.6.
20.3.3. Supports

Crushing of roof and floor strata by roof supports may liberate significant amounts of dust when the support is moved. This can be a particular problem on mechanized longwall faces that are equipped with powered hydraulic supports. As setting and yield loads of the supports increase so, also, does the amount of dust produced. The repeated lowering and raising of these supports can give a near continuous source of dust on longwall faces. Unless roof coal is left, this may be high in quartz content. The effect can be minimized by using wide-web roof beams or cushioning materials. Sheets of flexible material linking adjacent canopies have also been used to mitigate against roof dust.

Figure 20.6  An illustration of the effects of pick speed and pick depth of cut. Actual dust makes also depend on other factors including sharpness of picks, effectiveness of dust suppression and air velocities around the cutting head.

20.3.4. Blasting

Drill and blast remains the predominant method of mining in metal (hardrock) mines. The peak concentrations of dust and gases (Section 11.3.4.) that are produced by the larger blasts are usually too high to be diluted effectively by the normal ventilating airflow. This necessitates the mine, or part of the mine, being evacuated of personnel for a re-entry period during and after the blast. The length of the re-entry period can vary from half an hour to several hours for stoping areas, dependent upon the layout of the ventilation network and the velocities of the air. This is a classical example of isolating personnel from the dust.

The amount of dust produced depends upon a number of factors including

- the mining method
- the type of rock
- the choice of explosive
- the charge density and drilling pattern and
- the type of stemming.

Blasts that eject the fragmented material into an air space (e.g. open stoping) will tend to produce sharper but shorter lived peaks of dust than caving techniques. However, the latter may result in
more pulverized material capable of being entrained into the airstream during subsequent loading and transportation operations. Water ampoules have been employed as stemming in an attempt to reduce dust emissions from blasting operations.

Another technique is to place very fine but high capacity water sprays (fog machines) upwind of the blast before and during the re-entry period. The combination of increased humidity and fine water droplets assists in the agglomeration and sedimentation of dust particles. Spraying the muckpiles produced by blasting is advisable before loading commences.

Secondary blasting also produces short peaks of dust concentration. This is yet one further reason for employing methods of mining that minimize the need for secondary blasting.

20.3.5. Loading operations

This is another part of some mining cycles that can produce a great deal of dust whether the loading operations are carried out by slushers, load-haul-dump (LHD) vehicles or loading machines in headings. The dust arises from a combination of particles produced previously from the mining process and held within the muckpile, and those that are generated by further comminution during loading.

In addition to adequate (but not excessive) airflows, the primary means of combatting dust from loading operations are water sprays and ensuring as little disturbance as possible to the loaded material. The air velocity should not be less than 0.5 m/s at loading points. Abrasion of the floor by heavy slusher buckets should be minimized. It is preferable to employ lighter buckets in tandem operating at a speed of some 0.6 m/s (Sandys and Quilliam, 1982). Spray bars should be located at intervals along slusher paths and, particularly, at points of transfer between buckets.

Muckpiles in headings should be sprayed with water continuously or frequently during mucking operations except where hygroscopic minerals inhibit the copious use of water. In hot mines, pre-chilling of this water produces cooling as well as dust suppression (Section 18.3.5.2.). Steam injection into muckpiles and the addition of wetting agents into the water has also been found to be beneficial in some cases (Knight, 1985). Exhaust auxiliary ventilation is preferred for dusty operations in headings, employing a force overlap, if necessary, to deal with gas emissions at the face (Section 4.4.2.).

The skill of the driver of an LHD can have considerable influence on dust production. Choosing the best point to insert the bucket into the muckpile will result in filling the bucket with a minimum number of thrusts and with least disturbance to the material. Similarly, at the dump point, the muck should be tipped gently and not dropped from a height. This should also be borne in mind during the design of tipping operations from rail-mounted dump cars. Cones and chutes at dump points should be designed to minimize impact forces on tipped material.

20.3.6. Transportation and crushing

Dust is produced throughout most mineral transportation routes, including conveyors, transfer points, bunkers, skips, airlocks and vehicular traffic. Dust on the surfaces of conveyors may be re-entrained into the air due to vibration of the belt as it passes over rollers. Spillage returning on the bottom belt, if not cleared, will generate dust as the material is crushed against rollers. Similarly, an excessive use of water can result in dust adhering to the belt surface. This may subsequently be deposited under the conveyor during the return journey of the bottom belt. Belt scraper devices or brushes at the drive heads should be properly maintained and all accumulations of debris or dust should regularly be cleaned from under the conveyor and at return rollers. Conveyor structure should be inspected routinely and attention paid to damaged idlers and centering devices.
Vehicle arrestors on rail transportation systems should incorporate deceleration devices in order to avoid impact loads on either the vehicles or the transported material. Tracks should be adequately maintained and not allowed to develop sudden changes in direction or gradient.

The mineral transportation routes and mine ventilation system should be planned together in order to avoid, wherever possible, minerals being transported through an airlock. The high velocities that can occur over belt conveyors at airlock leakage points can cause excessive production of dust. This can be minimized by employing side plates and attaching a length of flexible material (such as old belting) on the conveyor discharge side of the airlock so that it drags over the surface of the conveyed material.

Unless the mineral is hygroscopic, it should be kept damp throughout its transportation through the mine. Bunkers and, wherever possible, conveyor transfer points and stage loaders should be shrouded and fitted with internal sprays. It is also useful to duct the air from such shrouds directly into return airways. Sprays or dribbler bars onto conveyors some 5 to 10 m before a transfer point are often more effective than sprays actually at the transfer point itself.

Ore passes in metal mines should avoid lengthy segments of free fall. Air leakage at dump and draw points should be into the ore pass and, hence, pull dust laden air away from personnel. This can be arranged by an opening into the ore pass and connected either directly or via ducting to a return airway. If this is not practicable then dusty air drawn by a fan from an intermediate point in an ore pass can be filtered and returned to the intake system.

Crushers in any mine are prolific sources of dust. Here again, sprays may be used on the material before, during and after the crushing process. This is another situation where it is particularly valuable to draw air from the crusher enclosure and filter it.

20.3.7. Workshops

Aerosols produced in underground workshops are likely to occur as oil mists, diesel particulate matter and welding fumes. The latter may be handled by exhaust hoods extracting air from welding bays and directing it into a return airway. Indeed, all of the airflows through workshops should, preferably, pass into return airways. The general arrangements for diluting and removing airborne contaminants from workshops are discussed in Section 9.3.5.

20.3.8. Quartz dust in coal mines

The availability of instrumentation that can discern the quartz content of mine dusts within each of a range of particle sizes (Section 19.4.7.) has led to the observation that airborne dust in coal mines often has a quartz content that is significantly higher than that of the coal seam being worked. Furthermore, the percentage of quartz becomes particularly high in the finer sizes including the respirable range (Ramani et al, 1988; Padmanabhan and Mutmansky, 1989). Coupled with the special danger to health of quartz dust, this has led to research aimed at discovering the causes of such anomalous appearances of quartz in airborne dusts of coal mines.

There would appear to be at least two explanations. First, roof and floor strata usually have a higher quartz content than the coal seam. Hence any fragmentation of those strata will cause emissions of quartz dust. This can occur by rock-winning machines cutting into the roof or floor, cross-measures drilling for roof-bolting or other purposes, development drivages out of the seam or exceeding the height of the seam, hydraulic roof supports and fracturing of roof or floor strata.

A second, less obvious, cause of the apparently anomalous percentages of quartz in the dust of coal mines is hypothesized to be the different comminution characteristics of coal and quartz (Section 20.3.1.). Fragmentation of the stronger and more brittle quartz minerals may result in a greater proportion of that dust being ejected into the air than is the case for coal. The greater degree of entrainment would favour the finer particles.
20.4. CONTROL OF DUST IN MINES

The initial decisions that affect the severity of dust problems are made during the stages of design and planning for the mining of any geological deposit. The methods of working, rate of mineral production and equipment chosen all influence the amount of dust that is generated and becomes airborne. The layout of the mine, sizes and numbers of airways, and the efficiency of the ventilation system dictate the rate at which airborne contaminants, including dust, are diluted and removed from the mine.

For an existing mine, there are four main methods of controlling the production, concentration and hazards of airborne dust:

- Suppression - the prevention of dust becoming airborne
- Filtration and scrubbing - the removal of dust from the air
- Dilution by airflow, and
- Isolation - separation of personnel from the higher concentrations of dust.

In general, good management and housekeeping at a mine assist greatly in maintaining control of the dust problem. These measures include planned maintenance schemes for equipment, quantitative ventilation planning, cleaning up spillage, rock debris and local accumulations of dust, and adequate supervision of work practices.

20.4.1. Dust suppression

It is difficult and often expensive to remove respirable dust from the air. Hence, every attempt should be made to prevent it from becoming airborne in the first place. Methods of achieving this are known collectively as dust suppression and are discussed in this section.

20.4.1.1. Pick face flushing and jet-assisted cutting

Figure 20.5 gives a visual impression of how a rock face is pulverized in advance of a moving cutter pick. Pick face flushing involves directing a jet of water at the pick point during the cutting process. This has been found to give markedly improved dust suppression when compared to conventional water sprays on the drums of shearsers, continuous miners or tunnelling machines. The water that feeds each jet can be channeled through conduits drilled in the bit holder and via a phasing valve that activates the jet only while the bit is cutting rock. Water filters are required to prevent blockage of the nozzles. A further advantage of pick face flushing is that the streak of incendiary sparks that often appears behind the pick in dry cutting is quenched. Hence, the incidence of frictional ignitions of methane is reduced greatly. Interlock switches may be employed to ensure that the machine cannot operate without the dust suppression water being activated.

A number of researchers have investigated the extension of pick face flushing to much higher water pressures, not only to further improve dust suppression but also in an attempt to produce a higher efficiency of rock cutting. The use of high pressure water jets alone, with or without the addition of abrasive particles, has had only limited success as a practical means of mining. However, combining the mechanism of cutter picks with high pressure water jets directed at the pick point has led to significant improvements in machine performance and the extension of mechanized mining to much harder material that, previously, could be mined only by drill and blast techniques. This technique is known as jet assisted cutting.

In addition to environmental enhancements, jet assisted cutting permits the same rate of comminution with reduced loading on the cutter pick. This results in a significant reduction in wear and, hence, less production time lost because of picks having to be changed. Furthermore, the total specific power (per tonne mined) required by the combination of a high pressure water pump and the cutting machine can be less than that of a conventional machine.
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The benefits of jet assisted cutting are attainable by increasing the water pressure but reducing the nozzle size in order to keep the flow rate no greater than that employed in conventional pick face flushing. This can be important in hot mines or where floor strata react adversely to water. However, it has been reported that there is little apparent improvement in levels of airborne dust until the water pressure attains some critical value (Taylor et al, 1988). This would appear to be in the range 10 to 15 MPa for cutting coal. After the critical water pressure is attained, a dramatic reduction in airborne dust can be expected. However, this levels out again at water pressures in excess of 20 MPa. Indeed, if the velocities of the jet and resulting spray are too high then re-entrainment can exacerbate dust concentrations. Work continues on the preferred location of the jet. Distances as small as 2 mm between the nozzle and the pick point have been suggested (Hood et al, 1991).

The environmental and operational benefits of jet assisted rock cutting arise from at least seven mechanisms (Hood, 1991).

(a) The pulverized rock immediately ahead of the pick point is wetted before it has an opportunity to become airborne.

(b) The cooling action of the jet reduces wear: the bits remain sharp for significantly longer periods of time and bit breakage is less frequent.

(c) Impact of the high velocity jet will produce an aerosol of very fine water droplets around the cutting head, thus enhancing the agglomeration and capture of airborne dust particles.

(d) The washing action of the high-energy jet removes the cushion of pulverized material quite efficiently. This allows the pick point to act on a much cleaner surface. The effect of a cushion of pulverized rock is to distribute the force exerted by the pick over a broader front, i.e. similar to that of a blunt pick, Figure 20.5(c). It is to be expected that the total amount of finely crushed rock would be reduced.

(e) Penetration of the water into natural cleavage planes in the material and ahead of the mechanical effect of the bit assists in pre-wetting dust particles that already exist within those planes.

(f) Frictional ignitions of methane are virtually eliminated.

(g) The total specific energy required for the rock cutting process may be reduced.

20.4.1.2. Water infusion

A technique of dust suppression that has been employed by some coal mining industries since the 1950's is pre-infusion of the seam by water, steam or foam. One or more boreholes are drilled into the seam in advance of the workings through which the fluid is injected. The migration of water through the natural fracture network of the coal results in pre-wetting of included dust particles. The success of the method is dependent upon the permeability of the seam and the type of coal-winning equipment employed. Good results have been reported where coal ploughs are used - these relying more upon coal breakage along natural cleavage than the cutting and grinding action of shearsers or continuous miners (Heising and Becker, 1980).

In practice, some in-situ experimentation is usually necessary to determine the optimum injection pressure and flowrate, and the time period of injection. Water pressures in the range 2 to 34 MPa have been reported with water volumes of 7 to 20 litres per tonne in South African coal mines (Sandys and Quilliam, 1982). Best results are obtained at fairly modest pressures but applied over as long a period as possible. British experience in coals of limited permeability indicated water pressures of 1.5 to 2.5 MPa and flowrates of 0.2 to 2 litres/min. If too high a pressure is used then the water flows preferentially along major planes of weakness. Hydrofracturing may
occur, resulting in weakened roof conditions during mining and, possibly, backflow along bed separation routes to give water inflows at the current working faces. Water infusion is not recommended in areas of weak roof/floor strata or in the proximity of faults or other geological anomalies. Steam and wetting agents have been employed in attempts to improve pre-saturation of the zone. Water infusion must also be expected to influence the migration of strata gas (Section 12.3.2.3.). Holes drilled initially for in-seam methane drainage may subsequently be used for water infusion (Stricklin, 1987).

20.4.1.3. Wetting agents, foams and roadway consolidation
Worldwide experience of surfactants used as wetting agents in dust suppression water has been highly variable. The technique has been employed since at least 1940 (Hartman, 1940). In addition to the use of wetting agents to enhance the effects of water infusion, they may be employed to improve the performance of sprays and also, at sufficiently high concentration, to produce a foam around a rock fragmentation process.

Rocks vary considerably in their wettability characteristics. If surfactants added to muckpile sprays are to be effective then they must be at a high enough concentration to cause penetration of the fragmented material within an acceptable time period (Knight, 1985). The potential effects of such concentrations on mineral processing should be considered carefully. Wetting agents added to sprays are considered to have three beneficial effects. First, the reduced surface tension allows greater atomization of the water - the droplets are smaller and greater in number, hence, improving the probability of capturing dust particles (Section 20.4.2.1.). Secondly, the existence of a liquid coating on dust particles will improve the chances of coagulation when two particles collide. Third, the molecular structure of surfactants tends to counteract electrostatic forces that may keep particles apart (Wang, 1991).

If a wetting agent is in sufficient concentration within a spray directed at a rock cutting device then a foam can be formed that enshrouds the comminution process. This assists in coating the fragments with a wetting fluid and in inhibiting entrainment of the dust into the air. Again, this approach has met with mixed success (Bhaskar, 1991). It also interferes with ventilation of the cutting head and should be used with caution in gassy conditions.

Accumulations of dust on roadway floors used for travelling in both underground and surface mines can become airborne when disturbed by traffic. Roadway consolidation involves the use of water, hygroscopic salts and binders to encapsulate the dust and maintain the floor in a firm but moist state. Flakes of calcium chloride or magnesium chloride may be employed with lignin sulphonate as a binder. The process involves raking and levelling the surface dust, and spraying it lightly with water until it is wetted to a depth of some 2 to 3 cm. The addition of a wetting agent may be necessary. The total amount of water required can be of the order of 40 litres per m². Free-standing pools of water should be avoided. The hygroscopic salt should be spread evenly at a rate that depends upon the mean humidity of the air. For flake calcium chloride this will vary from about 3.8 kg/m² at a relative humidity of 40 percent down to 0.1 kg/m² for a relative humidity of 90 percent. It is advisable to apply three quarters of the salt during the initial application and the remainder about one week later. The treatment will normally last for about six months although re-spraying with water may be required after three months. Sodium chloride (common salt) will be effective while the relative humidity remains above 75 per cent. In all cases, care should be taken against corrosion of equipment and, in particular, within the vicinity of electrical apparatus.

20.4.2. Removal of dust from air
The larger dust particles will settle out by gravitational sedimentation in the air velocities typical of most branches in a mine ventilation system. Unfortunately, the more dangerous respirable particles will effectively remain in suspension. Removing these from the air for large flowrates can be expensive. The choice of a dust removal system is dictated by the size distribution and
concentration of particles to be removed, the air flowrate and the allowable dust concentration at outlet. The size of any unit is governed primarily by the air volume flow to be filtered. Operational costs can be determined from the product of the pressure drop and air flowrate through the unit, \( pQ \) (Section 5.5.), and the means of supplying and filtering water in the case of wet scrubbers. Where high efficiency is required for large flowrates over a wide range of particle sizes such as the emergency filters needed on nuclear waste repositories (Section 4.6.), two or more types of filters may be arranged in series, each taking out progressively smaller particles. This prevents the finer filters from becoming clogged quickly and, hence, prolongs the life of the system before cleaning or renewal of filters becomes necessary.

The efficiency of any dust removal facility, \( \eta \), may be expressed either in terms of number of particles per m\(^3\) of air:

\[
\eta_p = \frac{\text{No. of particles in } / \text{m}^3 - \text{No. of particles out } / \text{m}^3}{\text{No. of particles in } / \text{m}^3} \tag{20.44}
\]

or in terms of mass of particles:

\[
\eta_m = \frac{\text{Mass of particles in } / \text{m}^3 - \text{Mass of particles out } / \text{m}^3}{\text{Mass of particles in } / \text{m}^3} \tag{20.45}
\]

In both cases, it is usual to further restrict the count of particles or mass to a specified size range. Hence, for protection against pneumonconiosis, it is preferable to employ equation (20.45) for respirable particles only, i.e. less than 5 microns equivalent diameter.

Devices to remove dust from air may be fitted to other pieces of equipment such as rock cutting machinery, along transportation routes, within ventilation ducting or as free-standing units to filter dust from the general airstream. In this section, we shall discuss principles of the devices that are most commonly employed to reduce concentrations of airborne dust in mine atmospheres, namely, water sprays, wet scrubbers and dry filters or separators.

20.4.2.1. Water sprays

Water is by far, the most widely used medium for conditioning mine air, whether it be for cooling (Section 18.3), dust suppression or dust filtration. Open sprays can also be employed to direct, control or induce airflows in order to protect machine operators from unacceptable concentrations of dust (Section 20.4.4.).

The important parameters governing the efficiency of a spray can be highlighted through an analysis of the capture of dust particles by water droplets. Consider Figure 20.7 which illustrates air passing over a water droplet with a velocity relative to the droplet of \( u_r \). The streamlines of air bend around the droplet. However, the inertia of dust particles causes them to cross those streamlines. Particles that lie closer to the centre line of motion will impact into the droplet and be captured by it.

We can conceive a flow tube of diameter \( y \) from which all particles are captured while particles that are further from the tube centreline will be diverted around the droplet. The efficiency of capture by a single droplet, \( E \), can be defined as the ratio of the cross-sectional areas of the capture tube to the facing area of the droplet:

\[
E = \frac{y^2}{D_w^2} \tag{20.46}
\]

where \( D_w \) = droplet diameter (m)
If there is a uniform dust concentration of \( n \) particles/m\(^3\) then the rate of capture of particles by one droplet of water is
\[
\frac{n \times u_r \times \text{area of capture tube}}{\text{m}^3/\text{s}}
\]
or particles/s; that is:
\[
\text{particles collected per droplet per second} = E n u_r \frac{D_w^2}{4}
\] (20.47)

In order to maintain consistency with the definition of dust concentration that we are using here (particles/m\(^3\)), it is preferable to restate this latter expression in terms of particles collected per cubic metre of air rather than particles captured per second. We can do this by dividing by the air flowrate \( Q \) (m\(^3\)/s).

Then rate of capture by one droplet \((dn/dt) = \text{rate of change of dust concentration}\) becomes
\[
\frac{dn}{dt} (\text{one droplet}) = E n u_r \frac{\pi D_w^2}{4} \frac{1}{Q} \quad \text{particles} \frac{s}{\text{m}^3} \text{ or } \frac{\text{particles}}{\text{droplet.m}^3} (20.48)
\]
where
\[
t = \text{time (s)} \quad (\text{negative as concentration is falling}).
\]

Now if water is dispersed in the spray at a volume flowrate of \( W \) (m\(^3\)/s) and the volume of each droplet is \( \frac{\pi D_w^3}{6} \), m\(^3\), then the rate at which droplets are formed and pass through the spray is
\[
\frac{W}{\pi D_w^3 / 6} = \frac{6W}{\pi D_w^3} \quad \text{m}^3 \text{ droplet/s} = \text{droplets/s} (20.49)
\]

Multiplying by the particle capture for one particle, equation (20.48), gives the total rate at which particles are captured per cubic metre of air:
\[
\frac{dn}{dt} (\text{all droplets}) = En u_r \frac{\pi D_w^2}{4} \frac{1}{Q} \frac{6W}{\pi D_w^3} \quad \frac{\text{particles}}{\text{droplet.m}^3} \frac{\text{droplets}}{s}
\]
\[
= \frac{3}{2} En u_r \frac{W}{D_w} \frac{1}{Q} \quad \text{particles} \frac{\text{m}^3}{s} (20.50)
\]
Now consider Figure 20.8. Dust particles and air pass each other effectively in counterflow with a relative velocity of $u_r$ such that they move through a separation distance $dx$ in time $dt$, i.e.

$$u_r = \frac{dx}{dt} \quad \text{m/s}$$

During that time, the dust concentration changes from $n$ to $n - dn$, i.e. the rate of change of dust concentration is $-dn/dt$ (particles/m^3s).

But

$$-\frac{dn}{dt} = -\frac{dn}{dx} \frac{dx}{dt} = -\frac{dn}{dx} u_r, \quad \text{particles/m}^3\text{s}$$

Combining with equation (20.50) gives

$$-\frac{dn}{dt} = -\frac{dn}{dx} u_r = \frac{3}{2} E \frac{n}{D_w} u_r \frac{W}{Q} \quad \text{or} \quad dn = -\frac{3}{2} E \frac{n}{D_w} \frac{W}{Q} dx \quad \text{particles/m}^3$$

Integrating over the complete effective length of the spray, $L$ (distance moved by particles plus distance moved by droplets (in counterflow) in the $x$ direction), gives the total number of particles removed between the inlet concentration, $N_{in}$, and outlet concentration, $N_{out}$ (particles/m^3)

$$\int_{N_{in}}^{N_{out}} \frac{dn}{n} = -\frac{3}{2} E \frac{W}{D_w} \frac{L}{Q}$$

$$\ln\left(\frac{N_{out}}{N_{in}}\right) = -\frac{3}{2} E \frac{W}{D_w} \frac{L}{Q}$$
\[
\frac{N_{\text{out}}}{N_{\text{in}}} = \exp\left\{-\frac{3}{2} \frac{E W}{D_w Q} L\right\}
\]  
(20.51)

Reference to equation (20.44) shows that the particle removal efficiency of the spray is given by

\[
\eta_p = \frac{N_{\text{in}} - N_{\text{out}}}{N_{\text{in}}} = 1 - \frac{N_{\text{out}}}{N_{\text{in}}}
\]

i.e.

\[
\eta_p = 1 - \exp\left\{-\frac{3}{2} \frac{E W}{D_w Q} L\right\}
\]  
(20.52)

Examination of this equation is most instructive in understanding the performance of sprays. The dust removal capacity of the spray increases with \(E\), the capture efficiency of each droplet. To be precise, this depends upon the nature of the flow and the relative sizes of dust particles and water droplets. However, a coarse approximation for fully developed turbulence, based on work reported by Jones (1978), can be assessed as

\[
E = 0.266 \ln(K) + 0.59
\]  
(20.53)

over the range \(0.2 < K < 4\) where \(\ln\) means natural logarithm and the dimensionless parameter \(K\) is:

\[
K = \frac{u_r \rho D_p^2}{9 \mu D_w}
\]  
(20.54)

where \(\rho\) = particle density (kg/m\(^3\))

\(D_p\) = particle diameter (m)

and \(\mu\) = kinematic viscosity of the air (Ns/m\(^2\)).

In particular, the capture efficiency increases with the relative velocity between the dust particles and droplets (\(u_r\)), the diameter (\(D_p\)) and density (\(\rho\)) of the particles (these three governing particle inertia) and increases further as the water droplets become smaller (\(D_w\)).

Returning to equation (20.52) reinforces the fact that the overall efficiency of the spray improves with smaller water droplets. A coarse spray of large water droplets will have very little effect on airborne respirable dust.

A parameter of basic importance in equation (20.52) is the water to air ratio (\(W/Q\)). Values in the range 0.1 to over 2 litres of water per cubic metre of air have been reported. The lower values produce poor efficiency of dust capture. However, if too high a value is attempted then the concentration of droplets may become so large that coalescence occurs. The larger droplets then lead to decreased efficiency. A practical range of \(W/Q\) for sprays and wet scrubbers in mines is 0.3 to 0.6 litres/m\(^3\). Tests on compressed air-powered atomizing nozzles have indicated an optimum \(W/Q\) value of 0.45 litres/m\(^3\) (Booth-Jones et al, 1984).

The last point to be gleaned from equation (20.52) is confirmation of the intuitive expectation that the spray efficiency is improved as the length (\(L\)) and, hence, time of contact between the air and the water droplets is increased.

In order to produce the finely divided sprays necessary to affect respirable dust, a number of methods are employed. The simplest technique is to supply high pressure water to the nozzles. Pressures of some 3000 to 4000 kPa applied across suitable nozzles give smaller droplets at
spray velocities high enough to cause air induction - surrounding dust laden air is drawn into the spray and thus improves the dust removal capacity of the unit. A variety of nozzle designs are available commercially. These control the shape as well as influencing the atomization of the spray. Full cone and hollow cone sprays have good air induction characteristics while fan shaped sprays are excellent at confining the dust clouds produced by shearsers and continuous miners. Atomization is further improved in some nozzles by impinging the high velocity jet against an impact surface located facing and close to the orifice. Another arrangement causes the water to rotate rapidly around an orifice before ejection. In all cases, it is particularly important in mining that nozzle designs should mitigate against blockage from particles either in the water supply or (in the case of machine- mounted sprays), thrown forcibly against the jet from an external source.

Compressed air-assisted sprays can produce fine atomization with droplets in the respirable size range. The water feed is connected into the compressed air supply close to the nozzles. The water enters the compressed airstream either by its own applied pressure or by venturi action. It is advisable to insert non-return valves into the water line. The combination of very high turbulence at the nozzles and expansion of the compressed air into the ambient atmosphere produces fine droplets.

Compressed air-assisted sprays can be further enhanced by the addition of a sonic device to the nozzle (Schröder et al, 1985). Air expands through the nozzle into a facing resonator cup where it is reflected back to complement and amplify the initial shock wave at the mouth of the orifice. An intense field of sonic energy is focused in the gap between the nozzle and the resonator cup. Water droplets issuing from the nozzle and passing through the sonic field are further broken down to respirable sizes and, indeed, to submicron diameters. Similar effects can be achieved by high frequency oscillation of pairs of piezo-electric crystals.

A high degree of atomization can be achieved without high pipeline pressures through impingement devices. A free-standing "fog machine" of this type may consist of a stainless steel disc spinning at about 3000 rpm. A low pressure water supply is fed to the centre of the disc. Centrifugal action causes the water to flow outwards over the surface of the disc to impact at high velocity on a ring of stationary and closely spaced vanes around the perimeter. A fan impeller located on the upstream side of the disc projects the fog-laden airstream forward. The same principle is employed in wetted fan scrubbers and in some industrial humidifiers.

20.4.2.2. Wet scrubbers
As the name suggests, these are devices that also employ water to achieve dust removal. However, in this case the water streams (or sprays) and the airflow are controlled within an enclosure designed to maximize the parameters that improve the efficiency of dust capture (equation (20.52)). Wet scrubbers bring dust particles into intimate contact with wet surfaces and within a highly turbulent mixture of air, water droplets and dust. They have become popular for mining applications as they require less maintenance than most other dust filters and can achieve respirable dust capture efficiencies exceeding 90 per cent.

Here again, we shall restrict our discussion to the operating principles employed in the most common wet scrubbers. Many competing devices are marketed and manufacturers' literature should be consulted to match performance with required duties, and to compare capital and operating costs.
The fibrous (or flooded) bed scrubber illustrated on Figure 20.9 is one of the most widely used devices employed in mine dust collectors. Stainless steel or other non-corrosive material is used as the fibre material. Water is either admitted along the top of the fibrous bed and allowed to trickle downwards through it or, preferentially, the water sprayed directly into the air upstream from the fibrous bed. The air follows a tortuous path through the bed while the inertia of the dust particles causes them to strike and adhere to the wet fibres. The efficiency of dust removal increases with the fineness of the fibres, the thickness of the bed and the velocity of the air. This must be balanced by the resistance of the unit to airflow and, hence, the operating cost. Efficiencies exceeding 90 percent for respirable dust can be attained.

The dust laden water collects at the bottom of the fibrous bed from where it is drained, filtered and recycled. Arrangements must be made to remove the effluent sludge and to supply make-up water. In all cases, wet scrubbers can be supplied with chilled water to achieve simultaneous cooling and dust collection. Again, filtration within the chilled water cycle is necessary.

A water eliminator is required by most designs of wet scrubber in order to remove residual droplets of water. Several different systems of water elimination are available in practice including a second fibrous mat, a series of wavy or inclined plates, turning vanes to induce swirl into the air and, hence, throwing droplets outwards towards the duct walls, or an egg-tray arrangement. Here again, droplet removal is achieved by impingement.

Figure 20.10 illustrates the principle of the wetted fan scrubber. Sprays upstream and/or at the facing boss of a fan produce droplets that are mixed intimately and at high velocity with air across and around the fan impeller blades. The polluted water collects around the internal surface of the fan casing for removal and recycling. The addition of a fibrous bed downstream from the fan gives a powerful combination of dust collection devices. A disadvantage of wetted fan scrubbers is the pitting that may occur on the impeller blades and requiring additional fan maintenance. Designs employing centrifugal as well as axial fans have been developed. Wetted fan scrubbers are well suited to lower airflows and have an application as in-line dust collectors in auxiliary ventilation ducting.

The venturi scrubber, depicted on Figure 20.11, has no moving parts. Sprays are located upstream and/or at the throttled section of a venturi arrangement. Air velocities through the throat are typically in the range 60 to 120 m/s with a high degree of turbulent mixing. This encourages the impaction of dust particles into water droplets. Venturi scrubbers are compact, simple and rugged, and can reach efficiencies of more than 90 percent. However, it is costly in operating power and is suitable for limited airflows only.
The **flooded orifice scrubber**, illustrated on Figure 20.12, also has no moving parts and has the additional advantage that there are no nozzles that might become clogged. Air from the inlet duct flows outwards beneath a lip that is submerged in water. Movement of the air causes extreme agitation of the water and entrainment of droplets. Collection efficiencies of more than 80 percent can be achieved with this system.

The preferred location for a dust collection device is as close as practicable to the source of the dust. The types of wet scrubbers outlined in the previous paragraphs are suitable as free-standing units or within ventilation ducts. However, attempts to attach them to coal or rock winning machines have shown them to be somewhat bulky for that application and insufficiently robust to withstand the rigours of a working face. A device that met increasing favour for shearers and continuous miners through the 1980's was the simple **high pressure spray fan or induction tube** (Jones, 1978; Sartaine, 1985; James and Browning, 1988; Jayaraman et al, 1989). This is illustrated by Figure 20.13 and consists of a water jet spraying into a tube of some 100 mm diameter. The water is supplied at pressures in the range of 6 to 12 MPa through a nozzle of about 1.5 mm diameter. The momentum of the fine droplets induces an airflow through the tube and is very effective in removing dust. A single spray within a relatively small tube appears to be more effective than multiple nozzles within a larger induction tube. Furthermore, hollow cone sprays give a better performance than solid cone sprays.
A series of 9 to 12 high pressure spray fans built into a longwall shearer drum is capable of promoting an airflow of up to 2 m$^3$/s around the drum and can give reductions in airborne dust concentrations of 80 percent compared to conventional pick face flushing using the same amount of water (James and Browning, 1988).

The direction of induced airflow is away from the coal face and towards the travelling track. Hence, dust laden air is drawn around the cutter picks and down the face side to the tube inlets. At the outlet of the tubes, the dust-laden droplets are discharged against deflector plates and fall on to the conveyor. Similarly, a number of induction tubes can be mounted in parallel on the boom of a continuous miner (Jayaraman, 1989). When employed in headings, the air induction may cause local recirculation and greatly improved ventilation of the cutter heads. Provided that adequate airflow is supplied to the face end of the heading, this will enhance the overall safety of the environment. However, legislative enforcement agencies should be consulted in industries where recirculation is prohibited.

The advantages of the high pressure spray induction tubes are that:

- they are simple, robust and have no moving parts
- they can be built into the machine structure
- they promote ventilation of the cutter heads as well as removing dust
- they give a good efficiency of dust capture and
- provided that the water pressure is maintained, there is little chance of blockage.

20.4.2.3. Dry filters and separators

There are many situations in subsurface ventilation systems where increasing the humidity of the air by the use of wet scrubbers is inadvisable. These include mines where heat and humidity is already a problem although cycling chilled water through wet scrubbers will reduce temperature, humidity and dust concentration simultaneously. Other difficulties that can arise from increases in humidity include clogging of hygroscopic minerals during transportation, roof control where the overlying strata is subject to rapid weathering, and where the mineral is subject to spontaneous combustion. In such circumstances, it may be preferable to employ dry filters to remove airborne dust.
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Figure 20.14 illustrates a fabric filter. The air passes through a fabric leaving dust particles adhering to the material or to the dust cake that builds up on the high pressure side. Air may flow from the inside to the outside of the bags as illustrated or in the opposite direction, in which case the bags are supported on an internal frame. The dust cake is dislodged at intervals of time by mechanical agitation or a reversed air pulse and falls to be collected in the hopper. The collected dust is either removed dry and bagged by a mechanical cleaning system or as a slurry produced by addition of water to the hopper.

The dust cake itself accomplishes most of the filtration and efficiencies of over 99 percent can be achieved in the submicron range. Airflow through the fine apertures of the dust cake is laminar. Hence, fabric dust collectors tend to follow a linear ($p = RQ$) relationship. The overall resistance of the unit arises from the combined effects of the dust-impregnated fabric and the dust cake. It is a straightforward matter to show that

$$ R = R_{\text{fabric}} + R_{\text{cake}} = \frac{\mu}{A} \left( \frac{x}{k_f} + \frac{m}{k_c A \rho} \right) $$

where $\mu$ = dynamic viscosity of air (Ns/m²)  
$A$ = surface area of filter (m²)  
$x$ = thickness of fabric (m)  
$k_f$ = permeability of dust-impregnated fabric (m²)  
$k_c$ = permeability of dust cake (m²)  
$m$ = mass of dust in the dust cake (kg)  
$\rho$ = density of the dust cake (kg/m³)

[The definition and units of permeability are explained in Section 12.3.2. However, manufacturers may assume a standard value of air viscosity and quote filter permeabilities in terms of m³/s of airflow through each (m² of area) for unit pressure gradient through the material (Pa/m), i.e. m³/s per m² per Pa/m.]
Equation (20.55) quantifies the increase in resistance as the thickness and, hence, mass of the dust cake builds up. This also increases the capture efficiency of the device. The pressure developed by the unit fan will rise and the air quantity will fall. An excessive pressure may cause rupturing of the filter fabric. The cake must, in any case, be dislodged before the airflow drops to an unacceptably low value. A backward curved (non-overloading) centrifugal fan operating on a steep pressure-quantity portion of its characteristic curve is advisable.

The simplest type of fabric cleaning mechanism is an electro-mechanical agitator. If operation of the unit can be interrupted every few hours (dependent upon dust loading) then the fan can automatically be switched off and the bags shaken by the agitator. More sophisticated units allow continuous operation by cycling the filtration and cleaning around several separate compartments.

Reverse flow cleaning involves a temporary reversal of air direction. This eliminates the mechanical linkages of the agitator system and is preferred for some types of fabric such as glass cloth where the severe flexing action of mechanical shaking may break the fibres. Pulsed jet reverse flow increases the efficiency of cleaning. Acoustic methods have also been employed to dislodge filter cakes.

The choice of fabric material usually lies between cotton weaves, felted fabrics or a synthetic such as polypropylene. The felted fabrics give an initially higher efficiency but synthetics are preferable where moist conditions or hygroscopic minerals may tend to produce a sticky dust cake. A newly installed bag will have a relatively low resistance. The initial mechanism is that dust particles will become lodged within the material. This increases both the resistance to flow and capture efficiency. Subsequent cleaning cycles will remove the dust cake but will have little effect on dust that has become impregnated in the material (more is dislodged from the smoother fibres of synthetic material). It follows that performance tests on a fabric dust collector should be delayed until dust impregnation of the material has reached steady state.

Two types of cyclone have been developed for dust removal, both of which can be operated dry or with the addition of water to improve capture efficiency. The conical cyclone operates by the dusty air being constrained into a helical vortex of reducing radius. Figure 19.4 was drawn to illustrate the conical cyclones used in dust samplers. Larger versions can be used as dust collectors. Dust particles are subjected to two opposing forces in a cyclone; the centrifugal force that tends to throw the particles out toward the wall, and drag of the air which tends to pull them inward toward the central air outlet tube. The greater the mass of the particle and the rotational velocity the more efficient the cyclone will become. Hence, the performance is enhanced for larger particles and as the physical size of the cyclone decreases. Cyclones are normally employed in groups for air cleaning. The centrifugal action is improved by arranging for the air to enter tangentially. It is essential to remove the dust from the base continuously in order to avoid re-entrainment. The finer particles that escape in the outlet air may be removed by a second cyclone or other filtration device connected in series.

The cylindrical cyclone imparts helical vortices to the airflow by means of turning vanes in a duct. The dust which concentrates and moves in helical fashion along the walls is collected and removed through an annulus formed by a second inner duct. The capital cost of cyclones is relatively low. They have no moving parts and are easy to maintain. However, the power requirements are such that they are constrained to applications of low airflow.

Electrostatic precipitators are used widely as air cleaners in buildings and for surface industrial applications such as the removal of fly ash from power station stacks or capturing aerosols in the chemical and metallurgical industries. Although a well designed electrostatic precipitator can reach capture efficiencies of over 99 percent in the submicron range, their need for high voltages prohibits their use in gassy mines and mitigates against their employment in other underground facilities.
The principle of operation of an electrostatic precipitator is that when an aerosol is passed through an electric field produced by a pair of electrodes then the particles will become charged and migrate towards one of those electrodes. For industrial applications, the active electrodes are charged to voltages between 20 and 60 kV while the dust collecting electrodes are earthed. The electric field is considerably enhanced in regions of sharp curvature on the electrode surfaces. For this reason, the active electrodes are often wires hanging vertically downward. The wires are usually charged negatively as this gives a more stable performance for heavy duty performance although ozone can be formed. High energy electrons are emitted from the negatively charged wires. Each electron collision with a gas molecule causes the ejection of two further electrons which go on to repeat the process. This escalating process produces an electron avalanche and is often accompanied by a visible glow; hence, the phenomenon is termed a corona. The gas molecules that have lost electrons become positive ions and migrate towards the negatively charged wires. However, further away from the active electrodes, the free electrons lose their kinetic energy to the extent that they are no longer capable of dislodging further electrons from gas molecules but are, instead, absorbed into those molecules. The electron avalanche ceases and the edge of the corona is reached.

The gas molecules are then negatively charged, i.e. negative ions, and migrate towards an earthed electrode. During that migration they become attached to dust particles which are also, therefore, drawn towards an earthed electrode and adhere by electrostatic attraction to the surface of that electrode. Upon contact, the particles begin to leak their charge to the earthed electrode. Other layers of charged particles arrive and build up progressively. They too will gradually give up their charge. However, the outermost layer of dust is always the most heavily charged and will be analogous to a skin compressing the underlying particles and causing the build-up of a dust cake. The dust can be dislodged into a lower hopper by rapping the earthed electrodes.

In tube electrostatic precipitators, a single wire forms the active electrode suspended in a metal cylinder which acts as the grounded electrode. However, for the larger flows found in industrial applications, the plate precipitator has become more common. This is illustrated in Figure 20.15. Air passes over the charged wire electrodes which are suspended between a series of grounded plates. The dust collects on the surfaces of the plates. For some applications, the mechanisms of dislodgment by rapping may be replaced by running a film of liquid down the plate surfaces or by periodically dipping the plates into a liquid bath.

The efficiency of an electrostatic precipitator can be determined by an equation first derived by W. Deutsch in 1922:

\[
\eta = 1 - \exp\left(-\frac{A u_e}{Q}\right)
\]

where \( A \) = area of plates (m\(^2\))
\( Q \) = airflow (m\(^3\)/s)
and \( u_e \) = electrical (ion) migration velocity (m/s) (see equation (20.28))

The electrical migration velocity depends upon the type of dust and varies between 0.02 m/s for fly ash to 0.2 m/s for gypsum. Although theoretical procedures have been derived for quantification of the electrical migration velocity, tables of empirical values have, to this time, proved to be more reliable (ASHRAE, 1988).
20.4.2.4. Personal respirators
Every effort should be made to maintain dust concentrations in subsurface workings within mandatory threshold limits and safe for the health of the workforce. A final line of defence is the personal respirator used to filter inhaled air. Two types are available. The first of these is a mask that fits around the nose and mouth. The filter is necessarily a compromise between dust removal efficiency and resistance. A respirator that requires more than about 150 Pa of pressure difference at normal breathing rates is unlikely to be tolerated by personnel. Furthermore, contact of the mask on the face can be irritating, especially in hot conditions. An improved version, sometimes called an airstream helmet, utilizes a belt-mounted battery to power a small fan. This passes air through a filter and up a tube to the helmet. The cleaned air flows downwards between a transparent visor and the face of the wearer. This device does not rely on breathing effort nor is there any direct face contact with the visor. It also provides eye protection with less visual impedance than that given by goggles or safety glasses.

20.4.3. Dilution and layout of the ventilation system

Despite the availability of dust collectors, dilution of mine dust by the mine ventilation system remains the primary method of controlling this hazard. The effects of airflow and air velocity have already been discussed in earlier chapters. Section 9.3.3 deals with airflow requirements for respirable and non-respirable dust while recommended air velocity limits are listed in Section 9.3.6. Exhaust systems of auxiliary ventilation are preferred for dust problems in headings (Section 4.4.) while overlap arrangements can also handle gas emissions. Furthermore, it is relatively straightforward to install in-line filters or dust collectors within ventilation ducts.
Controlled partial recirculation, where allowed by legislative authorities, coupled with dust filtration systems, can result in very significant reductions in general body dust concentrations (Section 4.5). The district ventilation systems discussed in Section 4.3 and designed to facilitate the dilution and removal of airborne pollutants in working zones apply equally well to respirable dust. Consideration might also be given to homotropal ventilation in which the airflow and mineral flow are in the same direction (Section 4.2.3.). As conveyors or other mineral transportation systems are then in return airways, any respirable dust they produce does not pass on to a working area. Furthermore, on a longwall face with uni-directional coal winning, few personnel need be on the downwind side of the machine. Despite these advantages, homotropal ventilation does have some drawbacks, particularly in mines with heavy gas emissions (Stevenson, 1985).

20.4.4. Separation of personnel and dust

In Section 20.3.4 we described the re-entry period after blasting in metal mines as a classical example of the separation of personnel from dust concentrations. Several other methods are available to reduce the exposure of individuals or groups to dust. The United States Bureau of Mines was active in developing this approach, particularly for the protection of the operators of longwall face equipment and continuous miners in room and pillar workings.

Airflow diverters of two types have been fitted to such machines. First, barriers have been added to shearerst in order to divide the face airflow before it reaches the location of the cutting drum. This is positioned such that it provides a split of relatively clean air to the shearer operator. A great deal of research has been conducted into the use of spray fans to control the direction and flow of air at continuous miners and longwall shearsers. Appropriate location and design of these triangular or cone shaped sprays not only assists in dust suppression but also ensures that airborne dust is diverted away from operators' positions (National Research Council, 1980).

Air curtains have also been employed to prevent dust clouds from reaching operators' positions, as well as assisting in the ventilation of cutter heads (Ford and Hole, 1984; Froger et al, 1984; James and Browning, 1988). The air curtains may be directed across the top, bottom and sides of the cutting zone. They are produced from tubes of about 10 mm diameter maintained at an air pressure of approximately 1.5 kPa. A 2.5 mm slot runs along the length of the tube with an attached guide plate angled such that air leaves the tube tangentially, clinging to the guide plate (the Coanda effect) until it is deflected into the required direction by a splitter. Entrainment of additional air assists in both the ventilating and dust control effects.

Another development that reduces dust exposure to machine operators has been the use of remote controls. These allow personnel to stand some distance from the mineral- winning machines while maintaining control by hand-held wireless units. Finally, studies leading to the reorganization of work practices have also promoted reduced dust exposure of face personnel (Tomb et al, 1990).

References


Jones, A.D. (1978). Experimental and theoretical work on the use of a high pressure water spray to induce airflow in a tube and capture airborne dust. MRDE Report No. 73, National Coal Board, U.K.


