Chapter 4

DEVELOPMENT OF A NEW PROTOTYPE SCRUBBER

4.1 INTRODUCTION

Field investigations carried out in four longwall faces showed that dust sources other than the shearer also contribute significantly to the total respirable dust concentration in the longwall face (details are presented in chapter 3) and these findings support earlier work by the U.S. Bureau of Mines (Jankowski, Organiscak and Jayaraman, 1991; Jankowski and Organiscak, 1983b). Most of the dust produced from other sources, such as support movement and face spalling, becomes airborne and quickly disperses into the walkway, thereby increasing the respirable dust concentration to unacceptable levels. A critical review of dust control research over the last three decades shows that whilst enormous effort has been directed at suppressing dust at the shearer, very little work has been done to reduce dust make from these other important dust sources (NCB, 1982; Jankowski and Organiscak, 1983a; Hewitt, 1990a; 1990b). The methods developed so far, to deal with this problem, such as use of filters and mats over the supports canopy, were labour-intensive, capital-intensive, and were found to be impracticable (Becker et al, 1988).

Therefore the control of these dust clouds is very important in order to reduce the dust exposure of longwall miners, which calls for the development of control techniques aimed at controlling the dust already airborne. In such cases, the installation of separating elements between the AFC and walkway area, such as local airflow systems, can be useful in reducing the face operators' dust exposure (McPherson, 1988; Hewitt, 1986a). Compressed air nozzles and air curtains have been tried in the past to provide the local airflow systems and separate the AFC from the walkway. These techniques reduced the walkway dust levels by between 25% and 70%. However, as both the techniques use only compressed air, the requirement of large quantities to compete with the primary face airflow made them uneconomical. In view of the above, the use of a multi-scrubber system along the walkway of the longwall face has been proposed.

Longwall dust control presents some unique problems. Some of the standard dust control techniques that are very effective in other mining situations may not work on longwalls. For example, machine mounted scrubbers have been highly successful in controlling dust from continuous miners. However, tests conducted on shearers with the available scrubbers were unsuccessful, as they were too large to be practicable. A detailed review of scrubbers, compressed air nozzles and air curtains has been given in section 2.5.9. The design and development of very compact and reliable scrubbers with low water usage, high capture efficiency and an effective mist eliminator is important for their successful application in a longwall face. Limited space in a longwall face dictates that the scrubbers also be compact.

The varied uses of scrubbers in longwall faces places different requirements on the manufacturers with respect to design and operation as well as performance. The manufacturers are not prepared, however, in the light of the high development costs, to offer a specialized manufacturing programme to the longwall mining industry, especially since the number of scrubbers required would inevitably be small and they would find little application in other sectors of the industry. Therefore, there is a need for the design and development of a prototype scrubber for use in longwall faces.

4.2 MULTI-SCRUBBER SYSTEM

4.2.1 Proposed concept

Since test results with a single scrubber proved unsuccessful to reduce dust levels in the longwall face, it was therefore decided to investigate the application of a multi-scrubber system in a longwall face, i.e. using a number of scrubbers along a face, to reduce miners' dust exposure (Aziz et al, 1993b). There are two ways in which scrubbers can be deployed in the multi-scrubber system. The first approach aims to reduce the total respirable dust concentration levels at the face, whereas the objective of the second approach is to provide a clean air zone along the walkway to reduce face operators' dust exposure.

The first approach involves using a number of high capacity (2 to 3 m^3/s) scrubbers to extract a large proportion of the respirable dust produced at the face. Modelling studies by Liu (1991) concluded that the minimum quantity of air through each scrubber should be between 2 and 3 m^3/s and that between 50 and 60 scrubbers are necessary to achieve a significant dust reduction in a longwall face. In addition, all the scrubbers would need to be operated throughout the shift to achieve the objective. However, this approach does not appear to be practicable for the following reasons: (i) the large space requirements of high capacity scrubbers which is a major constraint in a longwall face, and (ii) even if more scrubbers were installed in the face, only the scrubbers downstream of the shearer would be effective at any one time. Therefore, given that the longwall shearer moves from one end to the other, it is unlikely that all of the dust cloud would be captured by, and pulled through, one scrubber or even a series of scrubbers. It was therefore decided to investigate the second concept for reducing miners' dust exposure.

The second approach involves using a number of small capacity scrubbers to deliver cleaned air at high velocity into the front walkway area, to create a relatively clean air zone. The technique was aimed at reducing the dust in the operators' working area rather than reducing the dust levels in the entire face. It therefore requires between 12 and 18 scrubbers to be installed in the return part of the face and only a set of 4 to 8 scrubbers would need to be operated at any one time.

Another feature which favours the second concept of a multi-scrubber system is that the velocity contours at right angles to the longwall face show that the velocity is not uniform, being highest over the AFC area and lowest in the walkway. Therefore, if a high velocity split of air is produced by a multi-scrubber system in the low velocity walkway zone, the air will flow into the high velocity AFC zone, preventing dust diffusion into the low velocity walkway area. The air will also carry any support generated dust more quickly towards the face side, thus reducing the dust concentration in the walkway area.

As there was no scrubber available for use in a longwall face to begin research on the concept of a longwall multi-scrubber system, it was first necessary to design and develop a prototype scrubber in the laboratory. In a longwall face, the parameters of a multi-scrubber system which will determine the overall effectiveness of a scrubber are the size, capacity, location, dust removal efficiency, and exit velocity of clean air. They must be optimised to maximise the benefit from the system.

4.2.2 Design requirements of the scrubber

The design requirement of the scrubber system was to produce a relatively simple, efficient, small and practical unit suitable for operating in a longwall face. The other important features of the design were size, capacity, water consumption, maintenance and safety. The length of the scrubber had to be less than 1.3 m long, so that it could fit into one chock. To provide a clean split of air, the scrubber capacity had to be reasonably high, with a minimum of 0.5 m^3/s to compete with the face airflow of 15 to 20 m^3/s in moderately gassy longwall faces. As the scrubber was to be used in a multi-scrubber system, it was important to minimise the water consumption and design scrubbers without filters, so as to avoid the heavy maintenance involved in scrubbers with filters.

Originally, the proposed scrubber design consisted of a fan, an hydraulic motor and a dust capturing unit. As the design progressed it was found that it was not practicable to use fan powered scrubbers in a multi-scrubber system in longwall faces because of the following reasons:

(i) the size of the fan needed would be larger than 0.5 m ϕ x 1.0 m to provide the required quantity of air, and therefore would not fit in the chock shields.

(ii) the pressure developed by the small fans is in the range of 50 - 150 mm of water gauge, which is not sufficient for the efficient operation of compact scrubbers such as venturi scrubbers.

(iii) fans, if used in confined and continuously moving longwall chocks, are subject to fouling of the blades which may lead to methane gas explosions.

In view of the above, it was decided to develop an air powered venturi scrubber designed for use at longwalls, which used a small quantity of compressed air in conjunction with small amount of water . Air powered scrubbers are very sensitive to air pressure or restrictions on the suction and exhaust side, as they work on the principle of inducing secondary air. Therefore, effort was also directed towards the development of a very small, high velocity and minimum pressure drop water drop eliminator.

4.3 THEORETICAL CONSIDERATIONS

4.3.1 Particle characteristics

Dust particles formed by the grinding action of mining machines are dispersed into the air and remain suspended through the action of air currents. The particles range in size between 10^{-3} and 10^{3} μm, which represents a variation of 10^{6} in size and 10^{8} in mass. The size distribution of respirable dust at longwall faces have been discussed in sections 3.4.3, 3.5.2 and 3.7.2. Physical properties of of dust particles differ over this wide size range, as does particle behaviour in relation to these properties, e.g. resistance of the medium to particle movement, rate of evaporation and cooling, light scattering, and dominant mechanism of particle removal from the medium.

Particle concentrations are expressed either as a number or as a mass concentration. The number concentration of particles is the ratio of the number of particles in a given volume to the air volume. In the mine atmosphere, respirable particles concentration will be in the order of 100 to 1000/cm^{3}, with instantaneous/source concentrations being greater by several orders of magnitude. The particle mass concentration is defined as the ratio of mass of particles in a given volume to the air volume. The particle mass concentration can be determined by filtering a known volume of air and weighting the collected particles. Particles mass concentration in coal mines ranges from 0.2 to 50 mg/m^{3}.

Some of the non dimensional parameters that characterise the aerosol system (Patterson, 1984) are given below. These parameters are relevant to particle behaviour and collection mechanisms.

(a) Flow Reynolds Number (Re_a)

The flow Reynolds number is the ratio of inertial to viscous forces of a flowing fluid. When the Re_a < 2100, viscous forces dominate and the flow is laminar. For Re_a > 4000, the flow becomes turbulent.

The flow Reynolds number is

$$Re_a = \frac{V_a \rho_a D}{\mu_a} \qquad \ldots\ldots \qquad 4.1$$

(b) Particle Reynolds Number (Re_p)

Particle motion in the air stream is characterised by the particle Reynolds number which is defined by

$$Re_p = \frac{d_p (V_p - V_a) \rho_a}{\mu_a} \qquad \ldots\ldots 4.2$$

It is to be noted that the particle Reynolds number is dependent on the particle velocity relative to the air stream and the fluid properties. Typically, the particle Reynolds number will be in the order of 10^{-4} to 10^{2}.

(c) Knudsen Number (Kn):

Knudsen number is the ratio of the mean free path of gas molecules to the particle diameter and is given as

$$Kn = \frac{2\lambda_a}{d_p} \qquad \ldots\ldots \quad 4.3$$

From the kinetic theory of gases the mean free path, λ_a is

$$\lambda_a = \frac{kT}{2\pi P d_{mo}^2} \qquad \ldots\ldots 4.4$$

The value of the mean free path of air molecules at 20°C and 760 mm of Hg pressure is approximately 6.53 x 10^{-2} μm. For very small particles the gas appears discontinuous and the particles tend to slip between the gas molecules. This occurs when Kn > 0.1.

(d) Cunningham slip correction factor (C')

When the Knudsen number, Kn, is greater than about 0.1, particles slip between gas molecules and the resistance of the air is considered as discontinuous. In the Cunningham slip flow regime a correction factor is applied to account for the slippage. The correction factor includes thermal and momentum accommodation factors and is empirically fit to a wide range of Kn values.

The Cunningham slip correction factor can be calculated from

$$C' = 1 + \left[1.257 + 0.4\exp\left(-1.1\frac{d_p}{2\lambda_a}\right)\right]\frac{2\lambda_a}{d_p} \qquad \text{.. 4.5}$$

A simplified equation given by Calvert et al (1972) for use in air at normal pressure is

$$C' = 1 + \frac{6.21 \times 10^{-4}}{d_p}T \qquad \text{...... 4.6}$$

The Cunningham slip correction factor becomes negligible for particles larger than approximately 1 μm under normal conditions.

4.3.2 Principles of venturi scrubbing

Wet dust scrubbing is a process in which dust particles are transferred from an air stream to a liquid. This transfer process depends strongly on the size of the interfacial area between air and liquid and on the relative motion between the two fluid phases and between the dust particle and liquid.

a) Principles of dust particle collection

The collision of dust particles with water drops is discussed for the case given in Figure 4.1. The following assumptions are made:

(a) air and dust particles have the same velocity;

(b) air and water drops have the same flow direction;

(c) there is a relative velocity between air and water drop;

(d) the water drop has a spherical shape.

Fig 4.1a shows the movement of the air and the dust particles by streamlines and trajectories. Due to inertia forces, the dust particles approaching the water drop will not follow but cross the streamlines of the air and impinge on the drop. The possibility for dust particles to cross the streamlines of the air will increase with

- increasing inertia force of the dust particles, and
- decreasing radius of curvature of the air streamline

Figure 4.1 Dust particle collection by a liquid drop in a simple airflow field (after Brauer and Varma, 1981).

All those particles approaching the drop inside an area with diameter d_o will impinge on the drop as indicated in Fig 4.1c. The dust particles will either accumulate on the surface of the drop, in the case of poor wettability of the dust (Fig 4.1d), or penetrate the drop in the case of good wettability (Fig 4.1e). The dust particles impinged on the drop surface will move forward and accumulate at the rear stagnation point . Those dust particles that hit the drop close to the forward stagnation point will, however, remain there because the tangential velocity at the interface of the drop tends toward zero when the forward stagnation point is approached.

The collection efficiency of wet scrubbers has, for some time, been considered to greatly depend on the wettability of dust particles. However, experimental evidence proves that all dust particles that hit the surface of the drop will either penetrate the drop or adhere to the surface (Brauer and Varma, 1981). This process is independent of interfacial tension.

The diameter ratio d_o/d_d is called impingement factor:

$$\varphi_i = \frac{d_o}{d_d} \qquad \text{......4.8}$$

This factor can vary between 0 and 1 and has been shown to be a function of the inertia parameter/number K, which is defined by

$$K = \frac{2C' \rho_p R_p^{\,2} V_r}{9 \mu_a R_d} \qquad \text{......4.9}$$

Sometimes, this dimensionless group is also called Stokes' number.

Figure 4.2 describes the dependence of the impingement factor on the inertia number and indicates that the probability for impingement will increase with increasing relative velocity V_r, dust particle density ρ_p and diameter d_p due to the inertia of the particles. The chances of impingement will, however, diminish when air viscosity η_a and drop diameter d_d increase, because in this case the frictional forces will dominate and the gas carries the dust particles away.

The parameter Re_r is the Reynolds number of the air with respect to the collector and is defined as (Calvert, 1984)

$$Re_r = \frac{V_r \rho_a d_d}{\mu_a} \qquad \ldots\ldots \qquad 4.7$$

At high values of Re_r, the parting of the air streamlines occurs close to the collector. The sudden spreading of the streamlines at a high Reynolds number enhances the influence of particle inertia and therefore causes a higher collection efficiency.

Figure 4.2 Impingement factor plotted against the inertia number with Reynolds number as a parameter (after Brauer and Varma, 1981).

The impingement factor given in Fig 4.2 is of qualitative value only. Real conditions for the movement of air, dust particles and drops will be quite different from the assumed ones. For potential flow and for values of K greater than 0.2, the experimental values of inertial collection efficiency for spheres can be approximated by the correlation

$$\eta = \left[\frac{K}{K + 0.7}\right]^2 \qquad \ldots\ldots 4.11$$

(b) Atomization of water spray

Two types of atomization are likely to occur in the throat section of the venturi scrubber (Hesketh, 1973; 1974). The first, called drop type atomization, occurs when the liquid is introduced into the high velocity air stream from small diameter (< 1 mm internal diameter) nozzles, or when the liquid is introduced into the air stream in drop form. Cloud type atomization is the second type and results when the water is introduced as a stream (usually from nozzles that are more than 1 mm internal diameter). Cloud type results in the formation of much smaller droplets. However, the very small droplets formed by cloud type atomization join together by hydrostatic force without coalescing to form clouds which would move as a single system and have a much larger effective diameter. Using atomized droplet size, velocity and acceleration observations, Hesketh (1973) found that <10 μm droplets form clouds with an effective diameter of 170 μm to 500 μm, depending on the velocity.

Cloud atomization is desirable to produce sufficient inertial impaction targets for particulate matter collection and to produce a high surface area for absorption. It also keeps the droplet acceleration rate as low as possible which provides the greatest velocity difference between the particles being collected and the droplet target. Pneumatic atomization cannot be effective if the liquid introduced is not projected into the air stream, and then it will be atomized only when the air velocities are above critical.

A high airflow velocity is required in order to atomize the injected liquid by pneumatic Atomization. The minimum critical velocities required for the atomization of water by airflow can be found using the formula:

$$V_a\,(\text{crit}) = 1.7\left[\left(\frac{8550}{d_n}\right)^{1/2} + 15.3\right] \qquad \ldots\ 4.12$$

The clouds, moving as a whole because of the cohesive force between droplets, provide large effective impaction targets for the particulate matter and stop most of the particulate matter within 0.5 cm of the throat scrubbing liquid inlets.

(c) Particle collection by high velocity air

The interaction of dust particles with drops, described in this section, is typical of the situation occurring in the throat of a venturi scrubber. Figure 4.3 shows the situation where drops, dust particles and air move cocurrently at widely different velocities. The final section of the large size drop movement is sketched in figure 4.3 (a). The action of frictional forces, due to the high velocity gas stream, will enforce disintegration of the big drop into several smaller ones that assume and retain spherical shape. Intermediate steps of the disintegration process are illustrated in figures 4.3b and 4.3c.

This process involves the following steps:

a) deformation of spherical drops into ellipsoidal ones;
b) further deformation into the parachute lamella;
c) disintegration of the lamella into liquid filaments and drops;
d) disintegration of liquid filaments into drops.

Figure 4.3 Dust particle collection by water drops moving with very low velocity cocurrently with a high velocity air/dust particle stream (after Brauer and Varma, 1981).

The energy required for the deformation and disintegration process is provided by the high velocity air stream. Air flow and particle movement around an ellipsoidal drop is illustrated in figure 4.3 (b). Because of the small radius of curvature of the streamlines close to the rear of the ellipsoidal drop, the collection efficiency is quite high. This stresses the point that the directions of the drop and air/dust particle movement, as well as the shape of the drops, are of fundamental importance to particle collection.

The ellipsoidal drop is just an intermediate state of the disintegration process. With progressing drop deformation, another important intermediate state is reached in which the liquid is spread out in a parachute-like lamella. In this state, the surface of the drop available for particle collection has attained its maximum. The active particle collection surface is the inner surface of the parachute-like lamella. Close to this area, the air streamlines are reversed while the dust particles remain almost unaffected by this movement and impinge on the surface of the lamellae.

The parachute is characterized by the thin liquid lamella and also by the liquid torus at the rim of the lamella and, at the breaking points of the torus, by small drops. On account of inertial forces, the liquid torus will break away from the lamella and disintegrate into small drops. At the rim of the remaining lamella, a new torus will build up, break away and disintegrate into secondary drops. This process repeats itself until the originally large drop is split up into small drops containing the dust particles. Dust particle collection is most effective in the intermediate states of ellipsoidal drops and parachute-like lamellae.

4.3.3 Particle collection mechanism in the venturi scrubber

In a venturi scrubber, liquid is atomized by high velocity air at the entrance to the throat section. Particles from air are collected by water drops.

Calvert (1972; 1984) described particle collection in a venturi as follows:

$$\frac{dc}{c} = \frac{Q_w}{Q_a}\frac{4R_d}{55\mu_a}\rho_w V_a \eta df \qquad \ldots\ldots\ldots \quad 4.13$$

Equation 4.13 is modified for particle collection by water drops, based on the following assumptions:

1. Particles are collected only by atomized liquid.

2. The collection of particles by single drops is inertial and based on the relative velocity between the drop and the air. The inertial collection efficiency of the drop is approximated by

$$\eta = \left[\frac{K}{K + 0.7}\right]^2 \qquad \ldots\ldots 4.14$$

where K is the inertial impaction parameter

$$K = \frac{2C'\rho_p R_p^{\,2} V_r}{9\mu_a R_d} \qquad \ldots\ldots \qquad 4.14\ (a)$$

$$C' = 1 + \frac{6.21 \times 10^{-4}}{d_p} T \qquad \ldots\ldots 4.14\ (b)$$

The Cunningham slip correlation factor becomes negligible for particles larger than approximately 1 μm under normal conditions.

3. The acceleration of liquid drops is approximated by

$$x = \frac{55}{Re_r} \qquad \ldots\ldots 4.15$$

where

$$Re_r = \frac{V_r \rho_a d_d}{\mu_a} \qquad \ldots\ldots 4.15\ (a)$$

Assuming efficiency varies linearly with f,

$$\frac{\eta_a}{\eta} = \frac{f_a}{f} \qquad \ldots\ldots 4.16$$

The use of equation 4.16 in 4.13 resulted in the following equation

$$-\ln\frac{C_{out}}{C_{in}} = \left[13{,}500\,L + 1.2\,L^{2.5}V_a\right] X \left(\frac{\eta_a f_a}{2}\right) X\,10^{-4} \quad .. \; 4.17$$

Rather than using the assumption of equation 4.16, equation 4.17 has been modified to account for the point-by-point variation of collection efficiency with relative velocity.

Utilizing the definition

$$V_r = fV_a \quad ...... \quad 4.18$$

We obtain

$$K = \left[\frac{2C'\rho_p R_p{}^2 V_a}{9\mu_a R_d}\right] f = K_2 f \quad ...... 4.19$$

and

$$\eta = \left[\frac{K_2 f}{K_2 f + 0.7}\right]^2 \quad ...... 4.20$$

Substituting equation 4.20 in 4.13 gives

$$\int_{c_{in}}^{c_{out}} \frac{dc}{c} = \frac{4Q_w R_d \rho_w V_a K_2{}^2}{55Q_a \mu_a} X \int_f^0 \left[\frac{K_2 f}{K_2 f + 0.7}\right]^2 df \quad .. \; 4.21$$

Integration of equation 4.21 yields

$$\ln\frac{C_{out}}{C_{in}} = \left(\frac{4Q_w R_d \rho_w V_a}{55Q_a \mu_a}\right) f(K_2, f) \quad ...... 4.22$$

where

$$f(K_2, f) = \frac{1}{K_2}\left[-0.7 - K_2 f + 1.4\ln\frac{K_2 f + 0.7}{0.7} + \frac{0.49}{0.7 + K_2 f}\right] \quad .. \; 4.23$$

Equation 4.22 and 4.23 were used for calculating the theoretical efficiency of the scrubber.

4.4 GENERAL DESCRIPTION OF THE PROTOTYPE SCRUBBER

4.4.1 General description

The basic scrubber unit consists of an air powered venturi (Senior Australia Pty Ltd, 1991) water spray arrangement and a wavy blade type water droplet eliminator. Compressed air is used instead of a fan to move the air and and to help atomise the water. Primary compressed air enters the manifold of the venturi through a radial connection and is released through the annular gap to accelerate over the aerofoil section as shown in Figure 4.4. Secondary air is induced into the throat of the venturi scrubber because of the vacuum created by the injected compressed air. The ratio of induced air to primary compressed air used varies between 10 and 25 depending on the load conditions.

A non-wetted approach was used with water introduced at the throat rather than on the walls of the converging inlet section of the scrubber. A full cone wide angled spray nozzle with 1.6 mm diameter orifice was used in the scrubber. The nozzle was located 150 mm above the throat and was directed towards it. This arrangement ensured that the water spray covered the full pipe before the venturi throat and properly distributed the water. The water pressure was 1000 kPa (150 psi).

An impingement vane type water droplet eliminator (Figure 4.5), positioned approximately 0.6 m downstream of the venturi scrubber, removed the water droplets along with the dust particles. Two stages were used in the demister to remove the water from the cleaned discharge air stream. The demister vanes were made from galvanised zinc sheets. The demister box could be removed from the scrubber

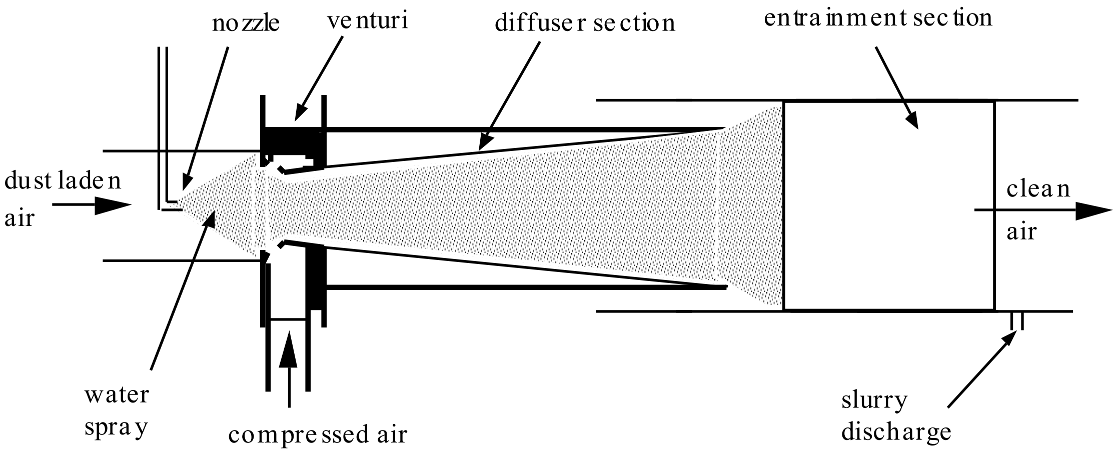

Figure 4.4 A schematic diagram of the prototype air powered venturi scrubber

Figure 4.5 Photograph of the demister used in the prototype scrubber.

very easily for repairs, if necessary. The slurry of dust particles was drained, by gravity, into a sump and was piped away from the scrubber.

The size of the scrubber unit is 0.17 m ϕ x 1.0 m long with a venturi throat of 100 mm diameter. The demister unit dimensions are 0.2 m x 0.2 m x 0.3 m. The total length of the unit was 1.2 m which easily fits in one chock shield. Figure 4.6 shows a photograph of the prototype scrubber unit.

4.4.2 Principle

The mechanism affecting collection of particles in the venturi scrubber are numerous. The physical phenomena involved are inertia, diffusion, electrostatics, brownian motion, nucleation growth and condensation. All of these affect particulate collection in a venturi scrubber, but it is generally agreed that the predominant phenomenon is inertia. The detailed mechanism of dust particle collection in the venturi scrubber is given in section 4.3.3.

The throat is the narrowest section of the venturi scrubber. The dust laden induced air is accelerated to high velocity (70 m/s) in the venturi throat section. This high velocity converts the static pressure head to kinetic energy. Water introduced to the throat is atomised by the high velocity air into very fine droplets and the high differential velocity between the air and atomised water droplets causes the airborne particles and fine water droplets to impact. In the expander section, the air slows down as the cross sectional area increases and some of the kinetic energy from the water droplets transfers back to the air stream pressure energy.

Figure 4.6 Photograph of the prototype scrubber developed in the laboratory.

A venturi scrubber removes dust from air more efficiently when the scrubbing fluid is effectively atomized. Cloud type Atomization has been used in this prototype scrubber to produce sufficient inertial impaction targets for particle collection and to produce a high surface area for absorption. It also keeps the droplet acceleration rate as low as possible and provides the greatest velocity difference between the particles being collected and the droplet target.

In the demister unit, curved profile blades are arranged to create separate parallel flow channels. The operation involves three stages: (i) the mist flow is divided at the bends because while the air flows through the bends, centrifugal forces prevent the water drops from following the air flow (ii) the inertial force created by the deflecting mist stream causes water drops to impinge on the blades and form a liquid film, and (iii) the film is forced towards phase separating downwind bends by the air stream and drops to the sump by gravity. Mist collection pockets at the bends were tried but it was found that more water drops were dispersed into the air stream due to the high air velocity and short demister length. Therefore, to channel the water film into the sump, some air quantity was allowed to leak towards the sump. This compact unit has a low pressure drop and a low clogging potential.

4.4.3 Advantages

Along with a high dust collection efficiency, the venturi scrubber also possesses most of the other characteristics desirable for a good underground scrubber. Some of the advantages of this prototype air powered scrubber are:

1. simple and very compact;
2. no fan or electric / hydraulic motor to maintain;
3. virtually maintenance free - no clogging, self cleaning;

4. high pressure water pumps are not required;
5. no electricity needed
   - very safe in high gas areas - no inherent permissibility problems;
6. can be easily installed in a longwall face;
7. uses very little water compared with a water powered scrubber;
8. does not split the air stream - no purge or bleed air;
9. uses facilities that are normally available in the face and does not need any special equipment for its operation.

4.5 LABORATORY STUDIES

A special wind tunnel facility was constructed in the laboratory so that a quantitative evaluation of the air powered venturi scrubber could be carried out. The facility is shown schematically in Figure 4.7. The test facility consisted of the following major elements. (1) ducting (2) measuring probes (3) dust feeding arrangement, (4) blower for dust dispersion (5) pitot static tubes and (6) Du Pont personal samplers. The test assembly is approximately 8 m long and the scrubber being tested was placed in the centre of a horizontal section of duct. Ducts of 300 mm diameter were used to keep frictional losses to a minimum yet maintain adequate transport velocity for dust tests. Ducts were fitted with a plexiglass side panel to allow observation of dust flow, samplers position *etc*. through the unit. Duct sections were made from 4 mm thick plastic with glued joints. This kept air leakage between sampling points to a minimum. The duct is designed for air velocity in the order of 5 to 10 m/s. These medium velocities helped to avoid sampling problems associated with high air velocities.

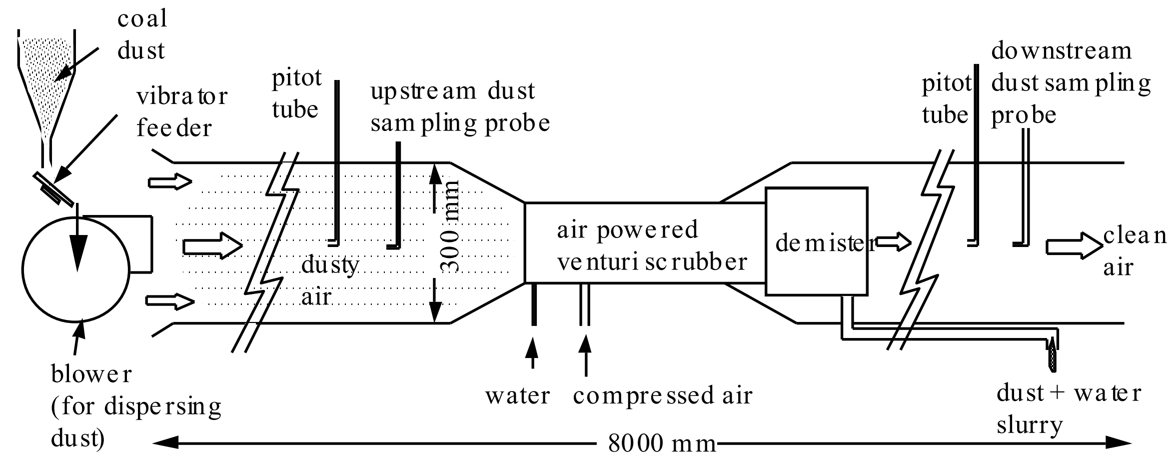

Figure 4.7 Laboratory test facility for evaluating prototype scrubbers.

A vibrator type dust feeder was located at the inlet, to provide a constant respirable dust flow between 1 and 100 mg/m^3 during dust collection efficiency tests. Dust from the vibrator was dispersed into the wind tunnel by a blower. The coal dust feed rate was controlled by a high turn-down ratio of the vibrator feeder thus providing a good control on dust flow. A blower was used to discharge dust in front of the ducting. With this dust feeding arrangement, a wide range of respirable dust concentrations and size distributions, typical of coal mine face operations, could be set up and maintained for long periods, thus enabling systematic evaluation of prototype scrubbers.

For the laboratory results to be more meaningful, it was decided to use coal dust which is similar to mine dust in size distribution. To prepare the coal dust for tests, coal pieces were ground in a ring pulveriser and then sieved through a 100 μm mesh. The fine pulverised dust has a size distribution similar to that of airborne coal mine dust, as indicated in Figures 4.8 and 4.9. Most tests were conducted with respirable dust concentration of between 8 and 30 mg/m^3. Various dust concentrations were achieved by changing the feed rate on the vibrator feeder.

Dust sampling cyclones and pitot static tubes were positioned in the ducts before, and after, the scrubber to measure dust concentration, pressure drop and air velocity upstream and downstream of the scrubber. The dust sampling cyclones were positioned 1 m upstream and 3 m downstream of the scrubber. A series of tests were conducted to determine the dust capturing efficiency of the prototype scrubber, and involved the measuring of airborne dust concentration with gravimetric samplers, before and after passing through the scrubber. The dust capturing efficiency was thus measured as a reduction of respirable dust concentration at the outlet.

During these investigations the samplers were operated for a period of 30 to 50 minutes and the weight of dust collected was determined after the experiment. Time averaged gravimetric dust concentrations over the entire sampling period were calculated based on the mass collected on the filters, sampling time and the pump flow rate.

The concentration of respirable dust was calculated using the following formula:

$$x = \frac{m_2 - m_1}{r.t} 1000 \qquad \ldots\ldots \; 4.24$$

where,
- x = concentration of respirable dust (in mg/m^3)
- m_1 = mass of filter before use (mg)
- m_2 = mass of loaded filter after use (mg)

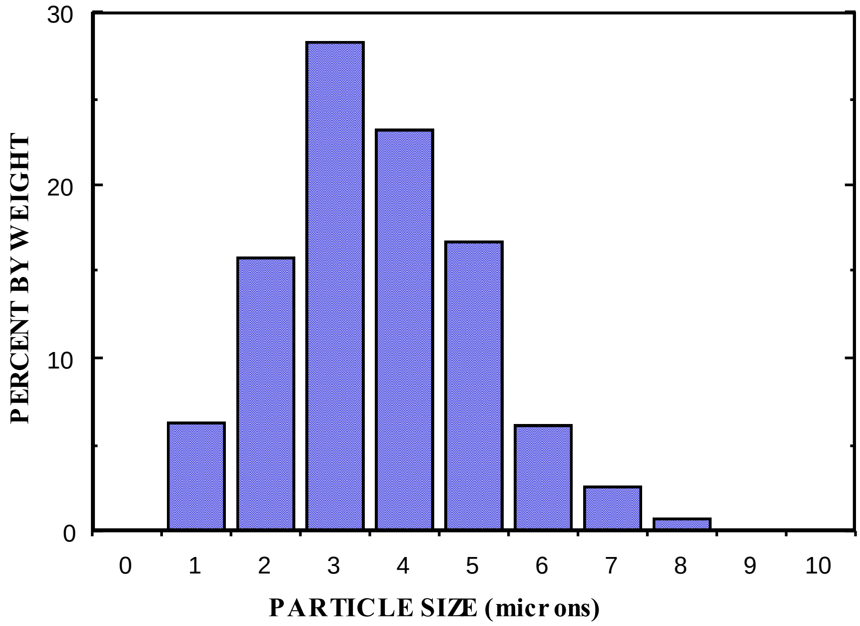

Figure 4.8 Typical size distribution of airborne respirable coal dust used in the laboratory experiments.

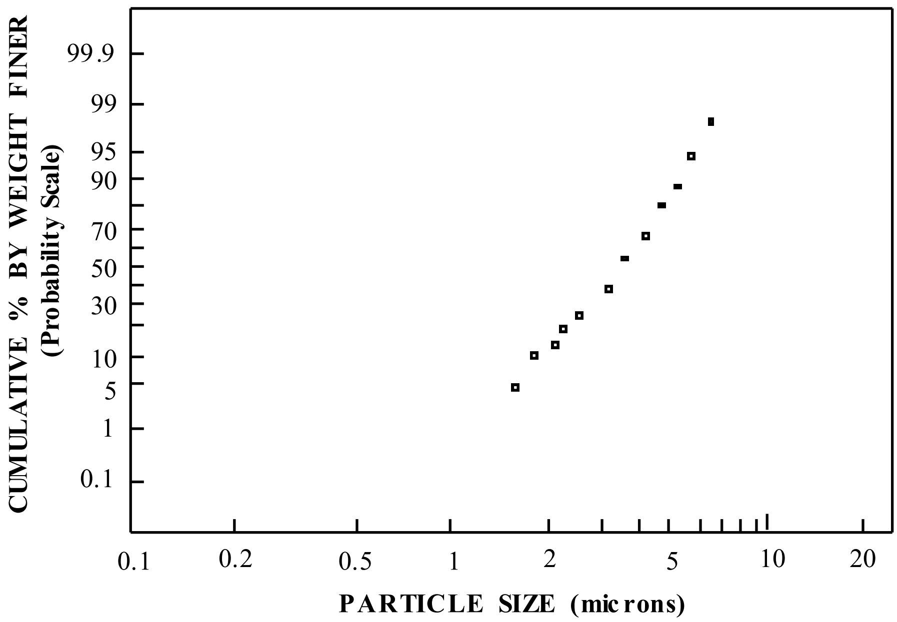

Figure 4.9 Typical cumulative size distribution of airborne respirable coal du used in the laboratory experiments on log-probability scale.

r = air flow rate through sampling pump (l/min)
t = duration of sampling (minutes)

The efficiency of the scrubber is calculated by

$$\eta = \frac{x_1 - x_2}{x_1} 100 \ (\%) \qquad \ldots\ldots \ 4.25$$

where, x_1 = respirable dust concentration at inlet to the scrubber (mg/m^3)
x_2 = respirable dust concentration at outlet of the scrubber (mg/m^3)

Airflow through the scrubber was measured with an anemometer and confirmed with pitot tube measurements in the ducting, and the pressure drop was measured using pitot static tubes and a manometer. Compressed air consumption and water consumption were also measured with flow meters connected to the lines. The rate of water flow through the nozzle was varied by changing the pressure to the nozzle and the nozzle orifice diameter. The air flow was varied between 0.3 and 0.7 m^3/s and water flow rate varied between 2.0 and 6.0 l/min.

4.6 RESULTS AND ANALYSIS

Results of the laboratory investigations carried out to determine the efficiency of the scrubber are given in Tables 4.1 to 4.2. It can be seen that at a water flow rate of 2.5 l/min for 0.55 m^3/s the scrubber efficiency is only 85%. By maintaining approximately the same air flow and increasing the water flow to 4 l/min, the efficiency increased to 90%. A further increase in the spray water rate to 6 l/min increased the scrubber efficiency to 92%. In summary, these experiments demonstrated 92% dust collection efficiency at a maximum air pressure differential and maximum water flow rate, i.e. 240 mm of wg and 6 l/min per 0.5 m^3/s respectively. The relatively low efficiency of 92% for this prototype scrubber is mainly due to the low water usage and very short length.

Table 4.1 Efficiency of the scrubber - Results of laboratory experiments (at 2.0 - 2.5 l/min water flow rate).

Sl. No.	Airflow (m^3/s)	Pressure drop (mm wg)	Water flow at 700 kPa (l/min.)	Upstream res.dust conc. (mg/m^3)	Down-stream res.dust (mg/m^3)	Scrubbing efficiency (%)
1	0.62	85	2.0	4.95	0.83	83.27
2	0.62	85	2.0	8.32	1.93	76.72
3	0.62	85	2.0	5.67	1.05	81.55
4	0.62	85	2.0	10.16	2.29	77.38
5	0.62	85	2.0	6.28	1.45	76.85
					Average =	79.15
6	0.58	110	2.5	7.20	0.90	87.50
7	0.58	110	2.5	7.55	1.02	86.49
8	0.58	110	2.5	9.70	1.60	83.51
9	0.58	110	2.5	10.30	1.40	86.40
10	0.58	110	2.5	12.31	2.14	82.61
					Average =	85.30
11	0.25	23	2.5	6.31	3.14	50.25
12	0.25	23	2.5	8.92	5.12	42.51
13	0.25	23	2.5	9.16	5.01	45.30
14	0.25	23	2.5	6.20	3.48	43.71
					Average =	45.44

Table 4.2 Efficiency of the scrubber - Results of laboratory experiments (at 4.0 - 6.0 l/min water flow rate).

Sl. No.	Airflow (m^3/s)	Pressure drop (mm wg)	Water flow at 700 kPa (l/min.)	Upstream res.dust conc. (mg/m^3)	Down-stream res.dust (mg/m^3)	Scrubbing efficiency (%)
1	0.55	160	4.0	12.60	1.10	91.27
2	0.55	160	4.0	10.40	0.80	92.31
3	0.55	160	4.0	14.20	1.20	91.55
4	0.55	160	4.0	8.10	0.80	90.12
5	0.55	160	4.0	15.35	2.21	85.57
6	0.55	160	4.0	18.50	1.40	92.43
7	0.55	160	4.0	14.90	1.60	89.26
8	0.55	160	4.0	9.40	0.80	91.48
9	0.55	160	4.0	19.34	2.69	86.09
10	0.55	160	4.0	14.28	1.72	87.96
					Average =	89.80
11	0.5	240	6.0	15.29	0.68	95.55
12	0.5	240	6.0	12.50	0.88	92.96
13	0.5	240	6.0	14.92	0.83	94.4
14	0.5	240	6.0	19.96	1.28	93.58
15	0.5	240	6.0	27.59	3.06	88.91
16	0.5	240	6.0	14.79	1.12	92.43
17	0.5	240	6.0	10.67	0.91	91.47
18	0.5	240	6.0	16.26	1.74	89.29
19	0.5	240	6.0	12.29	0.83	93.25
20	0.5	240	6.0	16.95	1.24	92.68
					Average =	92.45

Analysis of the results shows that the dust collection efficiency is a function of the water/air ratio for various throat velocities. Table 4.3 and Figure 4.10 shows that the efficiency of the scrubber increases with an increase in water quantity, and that a minimum of 5.0 to 6.0 l/min of water is required to achieve greater than 90% efficiency. A further increase in water pressure and quantity would increase efficiency, but it would not be practicable in some longwall faces owing to soft floor conditions.

The mist eliminator on the scrubber acts as a trap for water droplets carried with the air stream and was very efficient at less than 12 m/s air velocity. It also knocks down some dust particles, making it a second scrubber. When the air velocity was between 12 m/s and 17 m/s, some re-entrainment of water out of the primary drain sump was observed. This flow was stopped by adding a horizontal metal strip inside the demister frame which, in effect, extended the sump plate beyond the back edges of the demister vanes.

Table 4.3 Comparison of scrubber efficiency at different water flow rates

S.No.	water flow (l/min)	scrubber efficiency (%)
1	2.0	79.15
2	2.5	85.30
3	4.0	89.80
4	6.0	92.45

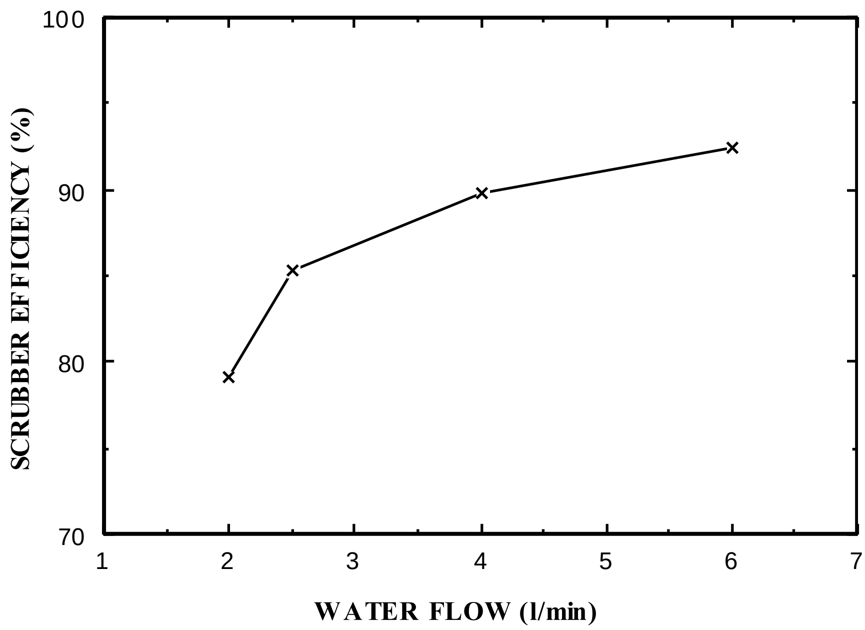

Figure 4.10 Efficiency of the prototype scrubber at different water flow rate

Table 4.1 also show the effect of varying the air quantity and pressure drop on the scrubber's efficiency. When the air quantity was less than 0.3 m^3/s (600 cfm) the efficiency was very low, because at such low airflow quantity, the velocity of air through the venturi throat is very low and cannot atomise the water droplets. Tests shows that a minimum of 0.4 m^3/s (800 cfm) air is required for effective Atomization of the water.

When the airflow was increased to 0.65 m^3/s (1300 cfm), under the same conditions, the efficiency dropped to 89% due to a low water/air ratio. More importantly, it was found that when airflow was greater than 0.65 m^3/s, or exit velocities were more than 20 m/s, the scrubber discharge still had some water drops. A larger demister was therefore needed which would not meet the design requirements. Thus in meeting the design criteria, the quantity of air flowing through the scrubber should be between 0.4 and 0.65 m^3/s (800 cfm and 1300 cfm). At this level of airflow, it was observed that the demister was effective and the effluent air stream was free of visible water drops.

As the overall efficiency of the scrubbers is dependent on the particle size distribution of the airborne dust, it was important to ascertain the size dependent efficiency of the scrubber. In addition, size fraction efficiency is most valuable for scrubbers intended for mining applications. Size distribution of the upstream and downstream dust samples from the scrubber are shown in Figures 4.11 - 4.13, and the efficiency of the scrubber over various sizes is shown in Table 4.4 and Figures 4.14 - 4.16. These results show that the removal efficiency of the scrubber is 63%, 88% and 97% respectively for 0.5 to 1.5, 1.5 to 3.0 and 3.0 to 7.0 micron size ranges. As the median size of the respirable particles in longwall faces is well above 3 microns, this scrubber can be successfully used to remove the dust in the longwall face.

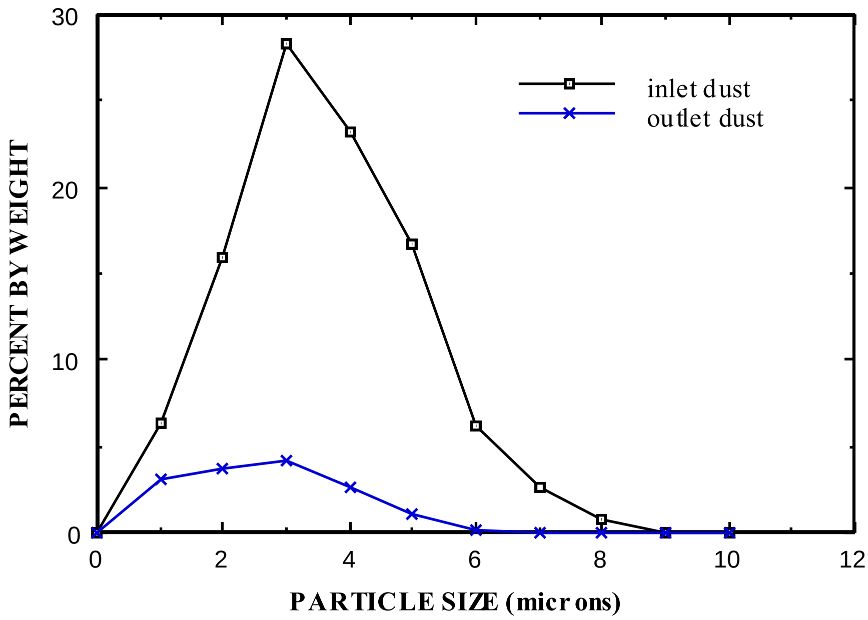

Figure 4.11 Size distribution of scrubber's inlet and outlet respirable (when the water flow through the scrubber is 2.5 l/min.

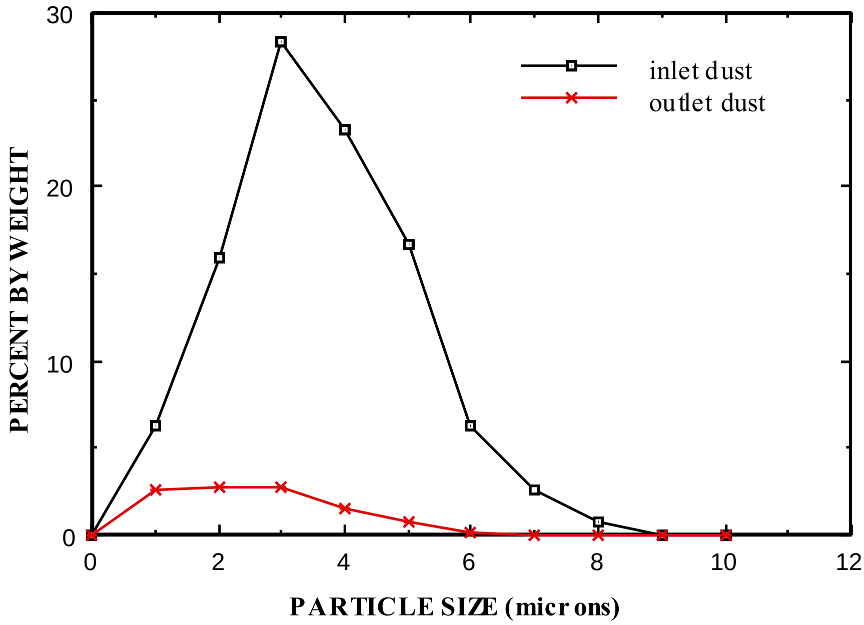

Figure 4.12 Size distribution of scrubber's inlet and outlet respirable d when the water flow through the scrubber is 4.0 l/min.

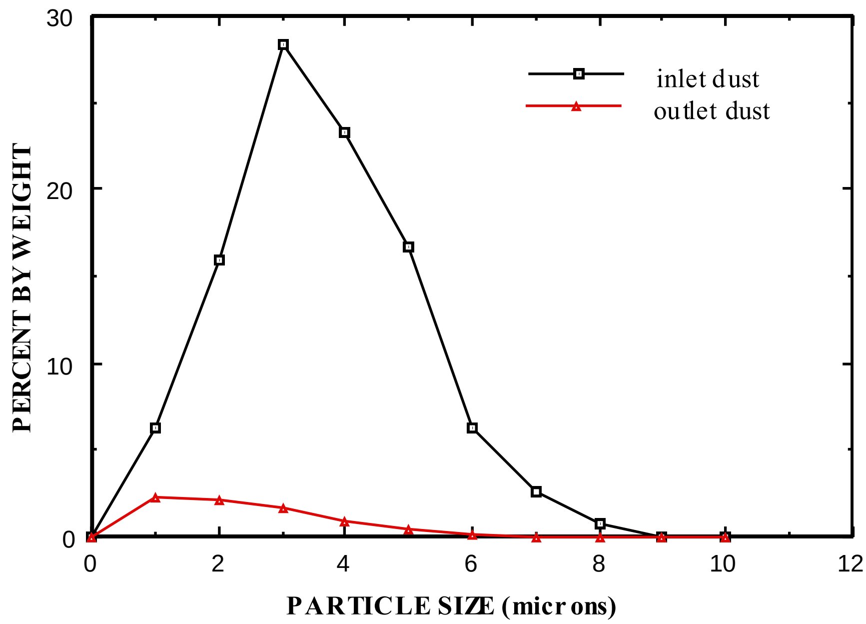

Figure 4.13 Size distribution of scrubber's inlet and outlet respirable d when the water flow through the scrubber is 6.0 l/min.

Table 4.4 Scrubber efficiency over various particle size ranges

particle size	collection efficiency at water flow of		
(µm)	(2.5 l/min)	(4.0 l/min)	(6.0 l/min)
1	49.8	58.3	63.5
2	76.6	82.8	86.6
3	85.1	90.2	93.9
4	88.9	93.1	96.2
5	93.1	95.3	97.0

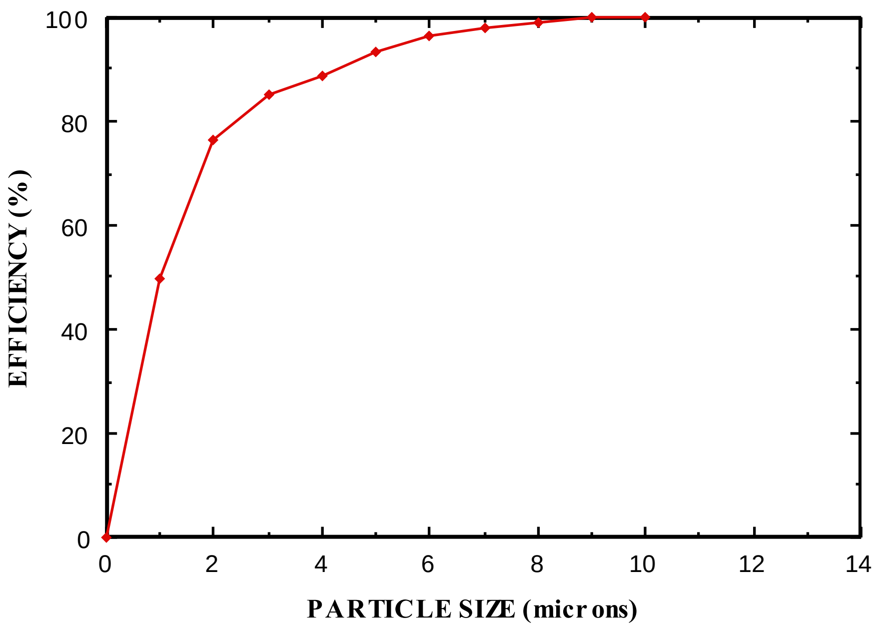

Figure 4.14 The size dependendent efficiency curve of the prototype scrubl
at a water flow of 2.5 l/min.

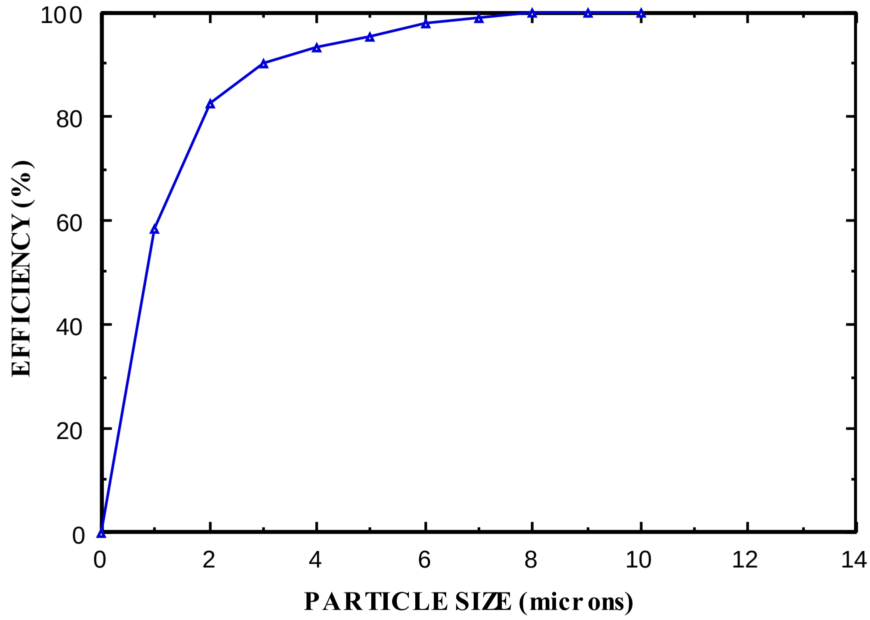

Figure 4.15 The size dependendent efficiency curve of the prototype scrub
at a water flow of 4.0 l/min.

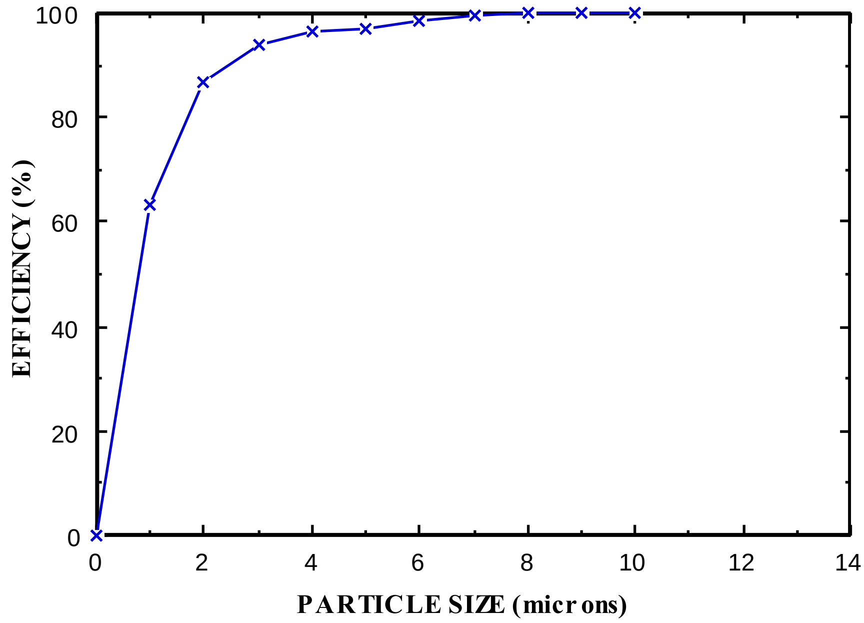

Figure 4.16 The size dependendent efficiency curve of the prototype scrubl
at a water flow of 6.0 l/min.

When the simplified theoretical collection efficiency equations (4.22 and 4.23), presented in section 4.3, were applied to the prototype scrubber, efficiency values between 75% and 99% were obtained for particles in the range of 1 to 5 μm as illustrated in Table 4.5 and Fig 4.17. The efficiency values shown were determined by using a mean water mist cloud size of 300 μm. The relative velocity value used was a rough approximation, obtained from the difference between the calculated air velocity in the throat and the water drop inlet velocity. The efficiency values shown in Figure 4.17 indicate that satisfactory results are theoretically possible for particle sizes down to 1 μm in diameter. The relationships between efficiency, water flow and particle size indicates that only a marginal change in the theoretical efficiency occurs with changes in the water flow for particles sized 8 μm and above. Conversely, for particles of approximately 1 μm the Equation 4.22 indicates that changes in water flow can cause major changes in the collection efficiency.

Table 4.5 Theoretical efficiency of the prototype scrubber

particle size	collection efficiency at flow of water		
(μm)	(2.5 l/min)	(4.0 l/min)	(6.0 l/min)
1	63.2	69.3	75.8
2	81.5	88.2	92.1
3	87.6	93.5	96.8
4	91.3	95.3	97.9

5	94.5	96.7	98.7

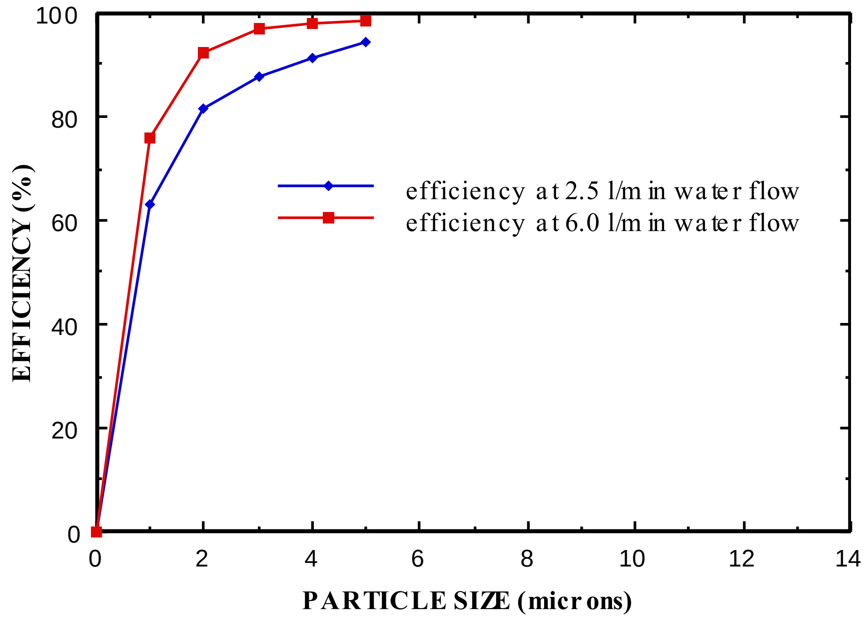

Figure 4.17 Theoretical efficiency curve of the prototype scrubber for various particle sizes at different water flow rates.

A comparison of theoretical and experimental efficiency values is given in Figures 4.18 and 4.19. It can be seen that the theoretical values were higher than the experimental values. The major reasons for this discrepancy are: (i) the majority of water drop clouds are far from uniform in size and are in the range of 100 to 500 µm (ii) the relative velocity between the water drops and dust particles is not constant throughout the length of the scrubber and is also extremely difficult to determine.

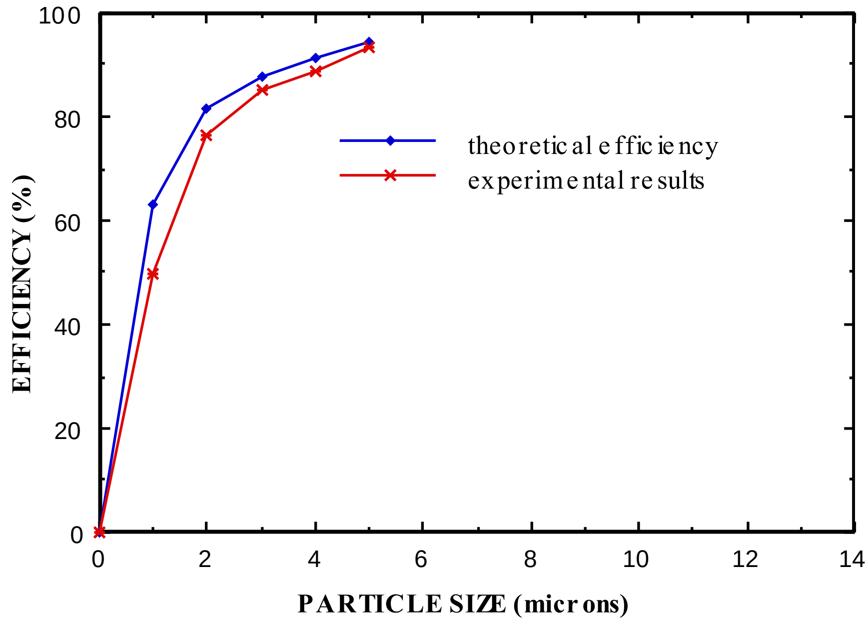

Figure 4.18 Comparison between theoretical predictions and experimental re
of scrubber's efficiency at 2.5 l/min water flow.

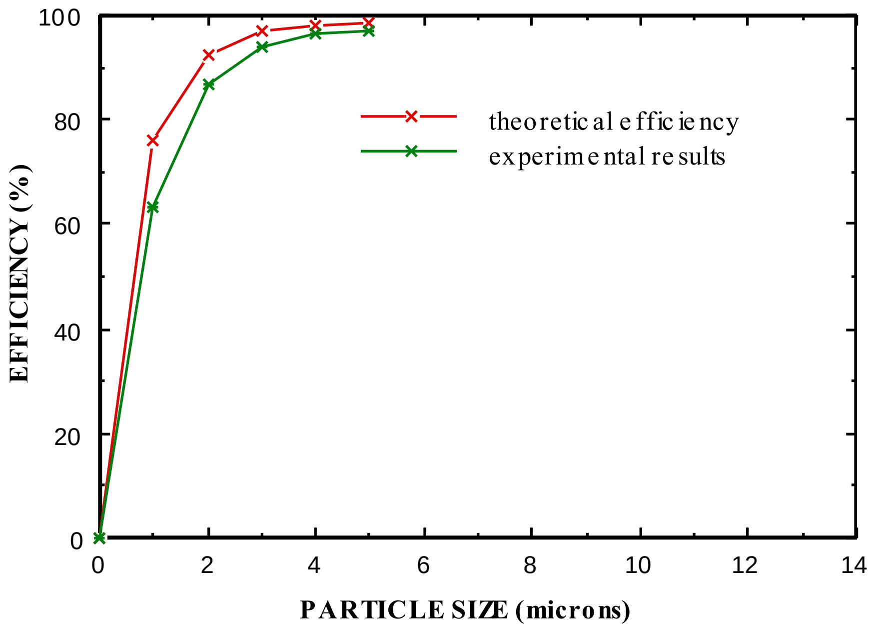

Figure 4.19 Comparison between theoretical predictions and experimental res
of scrubber's efficiency at 6.0 l/min water flow.

4.7 SUMMARY

A critical review of dust control research showed that very little research had been conducted into reducing dust make from principal sources of dust other than the shearer, such as from support advance, coal spalling from the face and goaf falls etc. During the field investigations carried out in two longwall faces (described in sections 3.4.2 & 3.6.1) it was observed that even though the shearer is the major source of dust, in many cases a considerable portion of the dust was produced during support movement and face spalling. Therefore there was a need to develop a new technique which could be used to reduce the respirable dust once it became airborne. With this objective in mind, the use of a multi-scrubber system along the walkway of the longwall face was proposed.

The aim of the multi-scrubber system proposed was to reduce miners' dust exposure along the walkway rather than concentrating on reducing total face respirable dust levels. The multi-scrubber system uses a number of moderate capacity scrubbers to deliver cleaned air at high velocity into the front walkway area, and thus create a relatively clean air zone in the face. As there was no scrubber suitable for use in longwall faces, it was first necessary to design and develop a prototype scrubber in the laboratory to investigate this concept.

The design requirement of the scrubber system was to produce a relatively simple, efficient, small and practical unit suitable for operating in the longwall face. The basic scrubber unit consists of an air powered venturi, a water spray arrangement and a wavy blade type water droplet eliminator. Compressed air was used, instead of a fan, to move the air and and to help atomise the water. A prototype air-powered venturi scrubber was developed for use in longwall faces. The total length of the unit was 1.2 m and can be fitted into one chock shield very easily. An impingement vane type demister was used in the scrubber.

A special wind tunnel facility was constructed in the laboratory to carry out a quantitative evaluation of the air powered venturi scrubber. Coal dust, which is similar to mine dust in size distribution, was used during the laboratory studies. During these experiments the maximum respirable dust collection efficiency of 92% was obtained at an air pressure differential of 240 mm of water gauge and a water flow rate of 6 l/min per 0.5 m^3/s of air. The relatively low efficiency (92%) of this prototype scrubber is mainly due to the low water usage and very short length. When air pressure and the nozzle water flow rate were not adjusted properly the scrubber performed very poorly. Results of the laboratory tests showed that air pressure, airflow and water flow are predominant factors in the scrubber's performance. The evaluation of prototype scrubber's performance in the field is discussed in chapter 5.