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STUDY OF CHARACTERIZATION OF SUBMICRON COAL PARTICLES DISPERSED IN AIR AND CAPTURE OF COAL PARTICLES BY WATER DROPS IN A SCRUBBING COLUMN

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STUDY OF CHARACTERIZATION OF SUBMICRON COAL PARTICLES DISPERSED IN AIR AND CAPTURE OF COAL PARTICLES BY WATER DROPS IN A SCRUBBING COLUMN

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in Chemical Engineering
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By
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Lexington, Kentucky

Director: Dr. Asit K. Ray, Professor of Chemical Engineering

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ABSTRACT OF THESIS

STUDY OF CHARACTERIZATION OF SUBMICRON COAL PARTICLES DISPERSED IN AIR AND CAPTURE OF COAL PARTICLES BY WATER DROPS IN A SCRUBBING COLUMN

Present day water spray based dust removal technologies do not effectively remove respirable submicron coal and silica dust particles in the underground coal mines causing Coal worker's pneumoconiosis (CWP). The objective of this research was to study the electrostatic charges present in the airborne coal dust in order to develop efficient water spraying based dust removal technology where water drops charged using ionic compounds and surfactants would be used to capture the oppositely charged coal particles. In an experimental scrubbing column, coal particles dispersed in an air stream by a Fluidized Bed Aerosol Generator were captured by water drops sprayed by an atomizer. Characterization studies performed using an Aerodynamic Particle Sizer and Aerosol Electrometer showed that airborne coal particles have a significant amount of positive charge with an average of 140 elementary units of charge. The capture efficiencies of the water drops evaluated were found to be higher than those predicted by previously determined mathematical models. It was predicted that apart from the effects of Brownian diffusion, interception and impaction, the effect of Coulombic attraction was present and the charge of the water drops was predicted to be between - 2 x 10^{-6} C and -2 x 10^{-4} C.

KEYWORDS: Capture Efficiency, Particle Scrubbing, Brownian Diffusion, Coulombic Attraction, Inertial Impaction

Utshab Chakravorty

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Date

Dedicated to my father, Mr. Chandranth Chakravorty,

my mother, Dr. Mrs. Bebi Chakravorty and

Miss Anurag Pramanik

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Chapter 1

Introduction

Coal worker's pneumoconiosis (CWP) or black lung disease has always been of serious concern for workers in the underground coal mines. Exposure to respirable coal and silica dust generated in the coal mines for long periods of time is the primary cause of this illness. Dust particles of sizes of 10 µm and lower are of maximum threat. Coal mine dust level standards have been lowered from 2 to 1 mg/m^3 in order to alleviate the dust levels and reduce their exposure to the workers. In spite of lowering of dust level standards, the present day dust suppression technologies based on water spraying are not efficient enough to prevent the dust generation caused by submicron dust particles. The problems lies in the fact that the water droplets generated by the sprays are neutral and the airborne respirable coal particles are hydrophobic in nature, which makes it difficult for the water drops to capture smaller coal particles. The hypothesis of this research is that coal dust particles contain a significant amount of inherent charge which can be used to effectively capture them using oppositely charged water droplets generated by an ultrasonic atomizer due to the Coulombic force of attraction.

The objective of this research was to study the charge and size distribution of coal particles (<10 µm) dispersed in an air stream by a fluidized bed aerosol generator and the effectiveness of drops generated by a water sprayer in an experimental gas scrubbing setup to capture the dispersed coal particles . The aim of this study is to experimentally determine the overall capture efficiency of a scrubber and the capture efficiency of a single water drop, compare the results with the efficiencies calculated from theories related to particle scrubbing and examine the possible role of Coulombic force of attraction in the capture of charged coal particles by the oppositely charged water drops. The research was performed in the following steps:

1. Study of the charge and size distribution of the coal particles was performed using a Fluidized Bed Aerosol Generator (FBAG), Aerosol Electrometer and

Aerodynamic Particle Sizer (APS). The FBAG was used to disperse the coal particles in an air stream, the APS would give the distribution of the number concentration of the particles and the Aerosol Electrometer would give the charge distribution of the coal particles.

2. The size distribution of the water drops generated by the ultrasonic atomizer was studied by performing experiments inside the experimental scrubbing column in the presence of counter current air flow in order to determine an accurate size distribution for calculating capture efficiency.
3. The scrubber capture efficiency and the capture efficiency of a single water drop were determined from the experimental results. The capture efficiency of a single water drop calculated at specific experimental conditions were compared with those obtained from the theoretical results based on previous literatures.

Chapter 2 gives a literature review discussing the water spraying techniques used for dust suppression in mines along with the theories developed and experiments carried out for determining the particle capture efficiency of normal as well as charged water drops. Chapter 3 describes in detail the experimental systems that have been used to characterize the coal particles and the coal particle capture using water droplets along with their operating principles and the experimental limitations. Chapter 4 explains the mathematical models used to calculate the charge per particle of the coal particles, capture efficiencies of the droplets as well as the scrubber efficiency and the assumptions used for the calculations. The basis of comparison between the experimentally calculated results and the theoretical results has been explained in this chapter. Chapter 5 presents the final calculated results in tabular and graphical formats along with the strengths and weaknesses of the experiments that have affected the results. Chapter 6 concludes the study discussing the interpretations of the study and its practical applications in the industrial arena.

Chapter 2

Background Literature Review

Dust suppression in coal mines has been a major problem over the past few decades with the increase in the diseases caused by respirable coal dust. Several dust suppression technologies predominantly based on water spraying has been developed till date. Theories have been developed for dust particle capture by water drops based on factors of Brownian diffusion, interception and impaction. At the same time laboratory experiments have been performed to test the effectiveness of these techniques and the validity of the theories developed. This chapter discusses the water spray based dust suppression techniques, particle capture theories developed and corresponding experiments performed till date.

2.1 Dust Suppression Techniques in Coal Mines

Use of water spray for dust suppression in coal mines has been a common technique for many years (Aziz, Johnston et al. 1989). The airborne coal dusts collide with the sprayed water drops and the coal particles adhere to the surface of the drop. The water drop settles down with the coal dust particles thus removing the dust from the mines. But water spray techniques are ineffective in capturing finer respirable coal dust particles for their complex microstructure causing reduced wetting abilities (Li, Lin et al. 2013). FTIR and XPS spectroscopy studies of the respirable coal dust particles show that these are strongly hydrophobic and form a layer of air around them that prevent them to be captured by the water drops (Yang, Wu et al. 2010). At the same time, when the surface of the droplet gets completely covered by the coal dust particles, they rebound off the droplet (Kilau 1993). These studies prove the ineffectiveness of the present day water spray techniques to remove respirable coal dust. Apart from using water spray, foam technology is also used as a dust suppressing agent (Wang, Wang et al. 2012). Recent geological studies have been performed by Schatzel (2009) and Schatzel and Stewart (2012) to understand the conditions of underground coal mines of the Appalachian Basin of U.S.A. Similar studies were performed by Yan-qiang, Yue-ping et al. (2011) who reviewed the research progress of the coal mines of China in terms of reducing the coal dust and the health hazards caused by it. These clearly indicate that more effective dust suppression is necessary to capture the finer respirable coal dust in order to prevent diseases like CWP.

2.2 Particle capture by water drops: review of theories

There are three primary mechanisms of dust capture by a single drop, Brownian diffusion, interception and inertial impaction according to Lim, Lee et al. (2006). The Brownian diffusion mechanism is responsible for the capture of finer submicron particles which come in the path of the falling water drop. The interception mechanism of particle capture occurs when although its path does not fall in the path of a water droplet, but its trajectory falls within one particle radius of the water droplet. The inertial impaction mechanism is occurs for particles larger than 5 µm with high Stokes number.

The theoretical model for calculating the capture efficiency in a gas scrubber for the collection of dust particles by sprayed water drops flowing in a horizontal column was given by Cheng (1973) as follows –

$$E_o = 1 - \exp\left(-\frac{3}{2}\eta\frac{\gamma W}{Q_g}\frac{L}{D}\right) \tag{2.1}$$

where E_0 is the overall collection efficiency of the scrubber, η is the capture efficiency of a single water drop, L is the length of the column, D is the average water drop diameter, W and Q_g are the water flow rate and air flow rate respectively and γ is a correction factor taking into consideration the loss of water drop caused by hitting the walls of the column due to the conical nature of the spray which is given by

$$\gamma = \frac{3r - 2\cot\alpha}{2r^3(1-\cos\alpha)} \tag{2.2}$$

where $r = S/R_D$, R_D is the duct radius and S is the projection distance of the spray and α is half the angle of projection. The underlying assumption of this theory is that only inertial impaction is the dominant collection mechanism and other mechanisms such as Brownian diffusion and interception are not significant. The effects of the relative velocity of the particle with respect to the water drops and the terminal velocity of the water drops are ignored in this theory. Particle removal efficiency of a horizontal scrubber was studied by Lim, Lee et al. (2006) and the governing equation was as follows –

$$E_o = 1 - \exp\left(-\frac{3}{2}\eta\frac{\gamma W}{Q_g}\frac{L}{D}\frac{V_t}{V}\right) \tag{2.3}$$

V_t is the relative velocity between particles and water drops and V is the terminal velocity of the water drops. The model however makes certain assumptions such as there is no interaction between water drops and the chamber gets completely filled with the water droplets as soon as they are sprayed.

Slinn (1983) obtained an analytical solution of the Navier-Stokes equation for the collection efficiency of a single particle due to Brownian diffusion as:

$$\eta_{diff}\left(d_p, D\right) = \frac{1}{Re\ Sc}\left[1 + 0.4Re^{\frac{1}{2}}Sc^{\frac{1}{3}} + 0.16Re^{\frac{1}{2}}Sc^{\frac{1}{2}}\right], \tag{2.4}$$

$$Re = \frac{DV\rho}{2\mu}, \qquad Sc = \frac{\mu}{\rho D_{diff}}, \qquad D_{diff} = \frac{k_b T C_c}{3\pi\mu d_p},$$

$$\text{and} \qquad C_c = 1 + 2.493\frac{\lambda}{d_p} + 0.84\frac{\lambda}{d_p}\exp\left(-0.435\frac{d_p}{\lambda}\right).$$

Here C_c is the Cunningham slip correction factor, T is absolute temperature, μ is the viscosity of air, ρ is the density of air, λ is the mean free path, D_{diff} is the diffusion coefficient and k_B is the Boltzmann constant.

Jung and Lee (1998) developed analytical solutions for particle capture efficiencies by the three different mechanisms of Brownian diffusion, interception and impaction. The diffusion dominant zone capture efficiency was modified neglecting minor terms by Jung, Kim et al. (2002) and Park, Jung et al. (2005) for the case of water drops as the following :

$$\eta_{diff}(d_p, D) = 2\left(\frac{\sqrt{3}\pi}{4Pe}\right)^{2/3}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{1/3} \qquad (2.5)$$

where α is the volume fraction of drop, σ is the viscosity ratio of water to air,

$$J = 1 - \frac{6}{5}\alpha^{\frac{1}{3}} + \frac{1}{5}\alpha^2, \qquad K = 1 - \frac{9}{5}\alpha^{\frac{1}{3}} + \alpha + \frac{1}{5}\alpha^2$$

$$\text{and } Pe = \frac{DV}{D_{diff}} \text{ (Peclet Number)}$$

A comparison between the capture efficiencies of equations (2.4) by Slinn (1983) and (2.5) by Jung and Lee (1998) for constant water drop diameters of 0.1 mm and 1 mm over a particle diameter of range 10^{-4} µm to 10^{0} µm was performed by the latter. The collection efficiencies predicted by both the equations were close to each other and it varied from 10^{-5} to 10^{0}. The limitations of these studies are that only efficiency due to diffusion was considered and the water droplet size was assumed to be constant at two cases of 1 mm and 0.1 mm which is not always the case while using an ultrasonic atomizer. The results do not give a realistic approach since there is a high possibility of the existence of a droplet size distribution between 1 mm and 0.01 mm and presence of coal dust particles mostly between 0.01 µm to 1 µm. However a better representation of the formula where all particles of sizes from below 0.05 µm up to 1 µm was done by H. T. Kim (2001) as follows:

$$\eta_{diff} = 0.7\left\{\frac{4}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{\frac{1}{2}} Pe^{-\frac{1}{2}} + 2\left(\frac{\sqrt{3}\pi}{4Pe}\right)^{\frac{2}{3}}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{\frac{1}{3}}\right\} \qquad (2.6)$$

In this case the Cunningham slip correction factor depends on the Knudsen-Weber equation:

$$C_c = \frac{2(1.664)\lambda}{d_p} \qquad for\ Kn > 2.6\ or\ d_p < 0.05\ \mu m,$$

$$C_c = \frac{2.609\sqrt{2\lambda}}{d_p^{\frac{1}{2}}} \quad for\ 0.15 < Kn < 2.6\ or\ 0.05\ \mu m\ < d_p < 1.0\ \mu m$$

where *Kn* is the Knudsen number. Jung, Kim et al. (2002) compared the modified equations with that of Slinn (1983). The advantage of this equation (2.6) for calculating the collection efficiency due to diffusion is that it takes into account the effects of induced internal circulation inside a liquid droplet. The limitation of the equation is that the collection efficiency is strongly dependent on the water droplet velocity. The particle diameter of coal particles used in this research is between 0.8 µm to 1.5 µm with the average size between 0.9 µm to 1 µm. Hence the formula used by Jung, Kim et al. (2002) is valid for this research for calculating the capture efficiency in the diffusion dominant zone.

The capture efficiency formula derived by Jung and Lee (1998) for the interception mechanism is given as :

$$\eta_{int} = \frac{(1-\alpha)}{(J+\sigma K)}\left[\left(\frac{R}{R+1}\right) + \frac{1}{2}\left(\frac{R}{1+R}\right)^2 (3\sigma + 4)\right], \quad (2.7)$$

$$where\ R = \frac{d_p}{D}\ is\ the\ interception\ parameter$$

The advantage of the equation (2.7) is that it is independent of the water droplet velocity. This formula was simplified by H. T. Kim (2001) assuming $R \ll 1 \quad or \quad \frac{R}{R+1} \approx R$ which resulted in :

$$\eta_{int} = \left[\frac{(1-\alpha)}{(J+\sigma K)}\frac{1}{D}\right] d_p + \left[\frac{(1-\alpha)}{(J+\sigma K)}\frac{(3\sigma+4)}{2D^2}\right] {d_p}^2 \quad (2.8)$$

For particle sizes larger than 5 µm, the dominant collection force is inertial impaction. Calvert (1984) and Licht (1988) gave the following equation for capture efficiency due to inertial impaction :

$$\eta_{imp} = \left(\frac{Stk}{Stk + 0.35}\right)^2 \tag{2.9}$$

$$where\ Stk = \frac{\rho_p {d_p}^2 (V - V_{si})}{18 \mu D} \quad (Stokes\ number)$$

where V_{si} is the settling velocity of the particle. Stokes number in this case is the determining factor, the higher its value more is the probability of capture by inertial impaction. However, H. T. Kim (2001) modified this equation to make it suitable for the particle distribution in the following way:

$$\eta_{imp} = 3.4(Stk)^{\frac{9}{5}} \quad for \quad Stk \leq 0.5 \tag{2.10}$$

and

$$\eta_{imp} = 1 \qquad for \quad Stk > 1 \tag{2.11}$$

These analytical solutions given by H. T. Kim (2001) provided a complete understanding of all the three types of efficiencies and the necessary equations (2.6), (2.8), (2.10), (2.11) required for every case depending on the particle size. These equations combined together were compared with the capture efficiency due to impaction given by Licht (1988) in equation (2.9). The comparison shows a good match between the two theories. However, the obvious limitation to this comparison is that in case of Licht (1988) only impaction forces are present whereas H. T. Kim (2001) used a combination of all three effects. An acute observation reveals that the capture efficiency reaches a minimum value close to the order of 10^{-4} as it reaches the d_p of 1 μm and again rises up to 10^{-1} as the particle size increases as well as decreases.

The overall capture efficiency of a single water droplet from all studies can be concluded to be the sum of the diffusion, interception and impaction efficiencies.

$$\eta = \eta_{diff} + \eta_{int} + \eta_{imp} \tag{2.12}$$

Equation (2.12) is a sum of all three efficiencies used by Park, Jung et al. (2005) to get an approximation for the derivation of analytical results. A comparison between the correct and approximated value was done by Park, Jung et al. (2005). The variation of the three efficiencies independently was compared over a range of particle diameter 10^{-2} to 10^{1} µm with a drop diameter of D = 1 mm and drop mass concentration of 50 g/m^{3} by Park, Jung et al. (2005). The results support the theories by showing that the efficiency due to Brownian diffusion varies from approximately 10^{-3} to 10^{-5} over the range of particle size and the efficiency due to interception also varies between 10^{-7} and 10^{-4} approximately. Whereas the efficiency due to impaction increases from zero to almost 1 as the size increases to 10 µm and it does not exist below 0.05 µm which justifies the theory of capture by impaction for larger sized particles. Park, Jung et al. (2005) also made a comparison between the theoretical results (sum of all three efficiencies), correct and approximated results. Once again the same observation can be made that the overall capture efficiency reaches a minimum value below the order of 10^{-4} at about 0.5 µm. The explanation is that at the minimum collision diameter the effect of Brownian diffusion reaches a minimum due to increase in the particle diameter. At the same time, the effects of interception and impaction mechanism begin to take place. The limitation of these results with respect to this research is that the drop diameter, D is 1 mm or 1000 µm, whereas in this research the D is between 2.5 µm to 90 µm. However, the experimental and theoretical equations used for calculation of overall scrubber efficiency and single water drop capture efficiency would be useful for this research to calculate them respectively. The results obtained in these literatures are very consistent with the theories developed and hence can be used in the range of concentration intended for this research and compared with the previous literature.

2.3 Particle capture by water drops: review of experiments

Pranesha and Kamra (1993), Kerker (1978) and Leong (1982) performed experimental studies of aerosol particle scavenging by falling water drops and measured the corresponding collection efficiencies. Pranesha and Kamra (1996) did a similar study using neutral water drops with larger drop sizes of 3-6 mm and larger particle sizes of 2-6 µm. Capture efficiencies as high as 60% was reported. The experimental results were compared with the theoretical results which were in agreement with the latter in the similar size range. Chate and Kamra (1997) also did similar experiments of particle capture using water drops. Similar to Pranesha and Kamra (1996), experiments proved that the results were in agreement with theoretical results of Slinn (1983). Pranesha and Kamra (1996) and Chate and Kamra (1997) both analyzed the effects of Reynolds number and impaction factor on the collection efficiencies since both the drop diameter and the particle diameters were an order higher than that used in the present. Vohl, Mitra et al. (2001) used a wind tunnel to study the effect of turbulence and laminar flow on particle capture by water drops. Zhao and Zheng (2006) did a Monte-Carlo solution of the aerosol scavenging by wetting taking into account the three effects of diffusion, interception and impaction. Recently Ladino, Stetzer et al. (2011) performed experimental studies taking into account the relative humidity factor in determining the collection efficiency. In this case, the aerosol particles were 0.05 – 0.33 µm and water drops were 12.8 – 20 µm (which is close to the size range used in this research). Capture efficiencies were reported as high as 110%. An improved dust suppression system using negative pressure secondary dust removal (NPSDR) technology was developed recently by Xie, Fan et al. (2007). In this new technology, ultrasonic dust suppression system was developed where water and compressed air was used to generate micron sized water drops to capture respirable dust in the mines effectively.

2.4 Role of charge in dust particle capture

The study of charge distribution of aerosol particles generated in the laboratory was performed by Marra Jr, Rodriguez et al. (2009) and Marra Jr. and Coury (2000) where the charged acquired due to natural process of aerosol generation as well as artificial methods of charging using corona charger were studied. Use of charged aerosol for dust particle capture was performed by Kraemer and Johnstone (1955) and Pilat, Jaasund et al. (1974). The theory of deposition of aerosol particles on a charged collector (cylinder and sphere) in an electric field was studied in detail and the analytical results were compared with experimental results by Kraemer and Johnstone (1955). Pilat, Jaasund et al. (1974) used electrostatic droplet spray scrubbers where water droplets of constant diameter 200 μm were negatively charged using a corona charger and collected dust particles between 0.01 μm to 10 μm, reporting droplet collection efficiency as high as 300 %. The scrubber overall efficiency was however reported as 17.4 % for uncharged droplets and nearly 100 % for charged droplets. Dhariwal, Hall et al. (1993) developed the novel method of using an electrodynamic balance to suspend a single charged droplet in a stream of submicron particles and measure the collection efficiency of the drop. Dhariwal, Hall et al. (1993) used the equation for collection efficiency of a droplet-

$$\eta = -4K_E \tag{2.13}$$

Where K_E is the Coulombic force given by

$$K_E = \frac{C_c Q_p Q_c}{3\pi^2 D^2 d_p \mu V_g \varepsilon_o} \tag{2.14}$$

Q_p and Q_c are the particle and collector charges, V_g is the free stream gas velocity, ε_0 is the dielectric constant of the surrounding fluid. After literature review and further investigation, Dhariwal, Hall et al. (1993) reported that the above equation was valid for all kinds of experimental conditions to measure collection efficiency. Dhariwal, Hall et al. (1993) compared their experimental and theoretical collection efficiency of a single drop with respect to the Coulombic force parameter (K_E) and reported collection efficiency as high as 1000. The comparison showed that the results of their study were in agreement with the theoretical results. Use of surfactants and wetting agents for control of coal dust was done by Tien and Kim (1997), Polat, Polat et al. (2002) and Zeller (1983). Polat, Polat et al. (2000) measured the electrostatic charges of sprayed droplets by surfactants such as Sodium-lauryl Sulphate (anionic), Cocoamine (cationic) and Triton X-100 (nonionic). Polat, Polat et al. (2000) reported a distribution of charges as a function of concentration. Polat, Polat et al. (2002) used these surfactants for the measurement of coal dust collection efficiency as a function of surfactant charge and concentration. Dust collection efficiency as high as 60% was reported which was however lower than the ones reported by Dhariwal, Hall et al. (1993). Wang, Leong et al. (1983), Wang, Stukel et al. (1986) and Wang, Stukel et al. (1986) did similar studies using charged accelerated droplets for submicron particle collection. They reported experimental collection efficiencies as high as 5 with droplet size of 100 µm. These studies show that electrostatic force has a more dominant effect on particle capture by charged water droplets and can increase the collection efficiency much higher than that by inertial and impaction forces.

2.5 Summary

As per the analytical solutions of H. T. Kim (2001), Jung, Kim et al. (2002) and Jung, Kim et al. (2003), the collection efficiency of a single drop can be calculated as the sum of the three efficiencies caused due to Brownian diffusion, interception and inertial impaction. The analytical results are valid in the size range of droplets (10 – 100 µm) and particles 0.8 to 1.5 µm. This study would use the Ultrasonic Atomizer for generating a distribution of drops according to which the final mathematical model for calculating the experimental collection efficiency needs to be modified. It can be predicted that the collection efficiency of droplets irrespective of the size would be below 1 due to absence of electric charging.

Chapter 3

Experimental Systems

The experimental systems used in this research for the purpose of coal particle characterization, water drop size distribution and coal particle capture inside the scrubbing column has been described in detail in this chapter. The operating principles of the instruments used and their specific applications have been discussed.

3.1 System of characterization of coal particles

The characterization of the coal particles contained in the air stream generated by the Fluidized Bed Aerosol Generator (FBAG), TSI model 3400, was performed using the Aerodynamic Particle Sizer (APS) and Aerosol Electrometer. Powdered coal particles used for this purpose were fluidized in the FBAG and dispersed in an upward air stream from the outlet. The volumetric flow rate of the air stream can be varied from 1 to 30 liters per minute using a rotameter placed on the instrument. The concentration of the coal particles can be varied by changing the motor speed of the chain that moves between the coal powder reservoir and the fluidizing chamber.

The air containing coal particles were passed at various flow rates and concentrations through a vertical chamber containing ports as shown in Figure 3.1. The vertical chamber was 3 inches in diameter and 2 feet tall. The ports were ¼ inch in diameter and constructed 4 inches away from the aerosol outlet of the FBAG. Through these ports samples of coal particles were taken out periodically over short time spans. These samples were analyzed using an Aerodynamic Particle Sizer (APS), TSI 3321 and an Aerosol Electrometer (3068 B) using samples at 1 liters per minute. Aerosol Instrument Manager Software was used to analyze the samples. The typical output of the APS on the Aerosol Instrument Manager is a bar graph of number of particles per cubic centimeters versus the diameter of the particles in microns. The Aerosol Electrometer however can take samples of aerosol from the analysis port at a flow rate that can be varied from 0.3 to 10 liters per minute and the software provides current in Femto

Amperes (fA) as a function of time. Both the outputs of the APS and electrometer provide values of mean and standard deviation. Using these two data, the charge per coal particle can be calculated. Another kind of experiment was done using only the FBAG. In this experiment, at certain volumetric flow rates of the air, the motor speed of the chain was changed in a periodic manner. In these experiments, bilayer filter papers were used in a sealed chamber. The mass of coal particles collected in the pores of the filter papers was determined by weighing the filter paper after a definite time interval. A calibration was made at a particular flow rate by varying the motor speed and calculating the mass concentration by weighing the collected mass.

3.1.1 Experimental Setup

Figure 3.1 provides schematic of the experimental setup for the first set of experiments. As shown, the coal particles were dispersed in the air stream by the FBAG and were passed through seal vertical chamber of 3 inch diameter. Two ports of nominal diameter ¼ inches were present through which the samples were taken in for analysis by the APS and the Aerosol Electrometer. The aerosol exited the chamber through the exhaust.

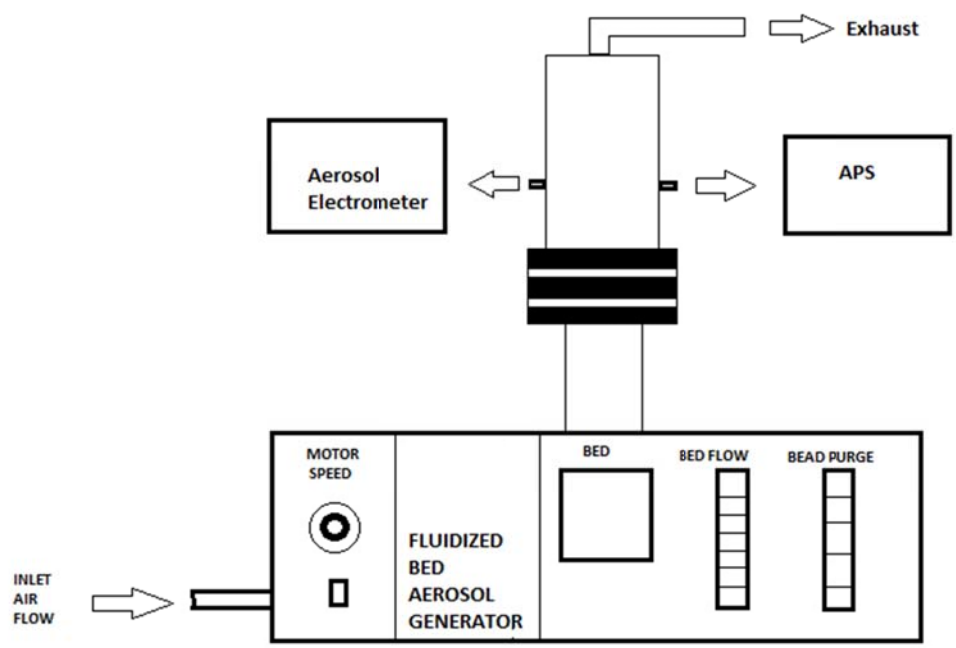


Figure 3.1 – Description of experimental setup for first set of experiments

The Figure 3.2 shows the schematic of the second experiment. An air stream containing coal particles was flowed through sealed vertical chamber of 3 inch diameter. This chamber had filter papers so that the coal particles can be trapped within the filter papers. By measuring of difference in the weights of the filter papers before and after an experiment, the mass concentration of the aerosol stream can be determined. The air stream left the chamber through an exhaust.

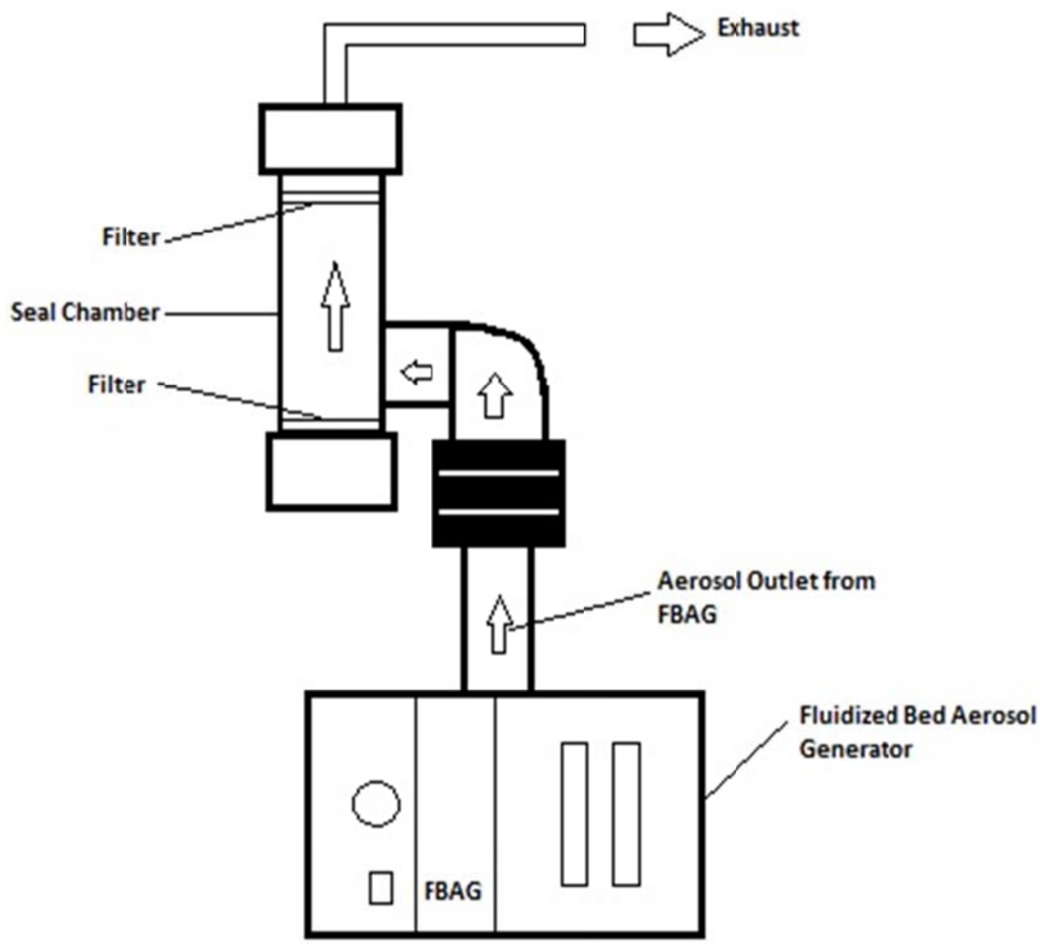
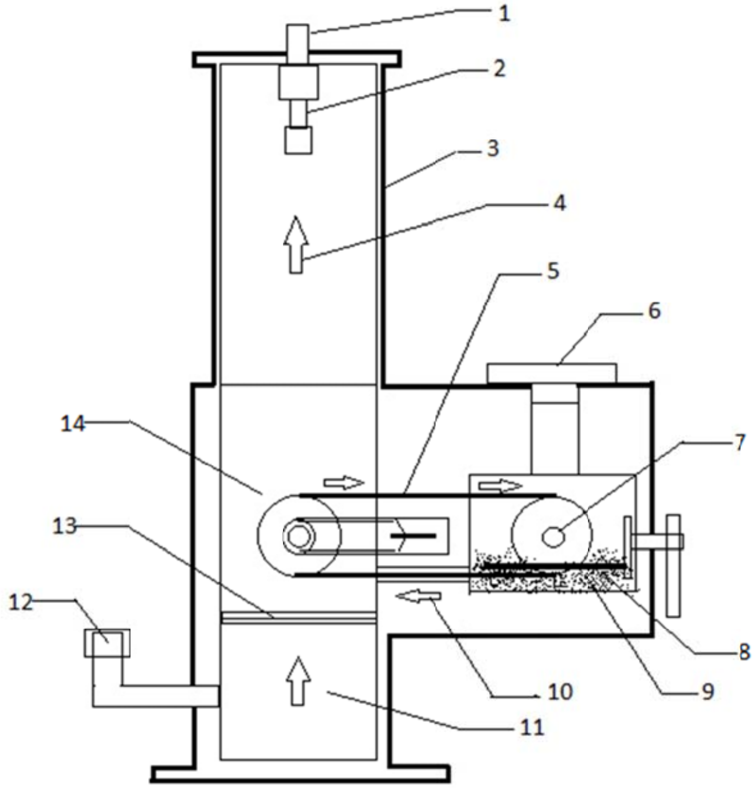


Figure 3.2 Description of experimental setup for second experiment

3.1.2 Description of instruments

3.1.2.1 Fluidized Bed Aerosol Generator

A schematic diagram of TSI model 3400 Fluidized Bed Aerosol Generator is shown in Figure 3.3. It explains the principle and working of this instrument in detail. Towards the right is a reservoir where the powdered coal is present. The powder reservoir needs to be filled from time to time with coal powder to get consistent concentration of output of mass of coal particles from the machine. The indication that the reservoir needs to be filled on coal is when the output concentration (found out from the APS reading) becomes lower than expected, especially at higher flow rates and higher motor speeds. Towards the left is the fluidized bed chamber where the fluidization takes place. It contains bed materials over an air filter. Below this chamber is the air plenum chamber through which the air enters and moves up into the fluidizing chamber. The bead chain connects the fluidized bed chamber and the powder reservoir. A motor drives the bed chain at a variable speed. The movement of bead particles through the powdered coal deagglomerates the coal power. The deagglomerated coal powder is brought to the fluidized bed chamber by the bed chain. The air flow from below carries the coal powder upwards through the elutriator to the aerosol outlet. There are two parameters of the aerosol flow that can be varied. One is the air flow rate or bed flow which can be varied from 1 to 30 liters per minute by a rotameter placed in front of the machine. There is also a second rotameter present just beside the main rotameter which is called the bead purge. This should always be maintained at 2 liters per minute. The function of this air line is to blow off the coal particles from the bed chain before it enters the powder reservoir so that fresh coal particles are taken up by the bed chain and brought to the fluidized bed chamber. The second parameter that can be varied is the speed of the bed chain or motor speed. The higher the speed of the bed chain, the higher will be the mass of the coal particles dispersed in the air stream.



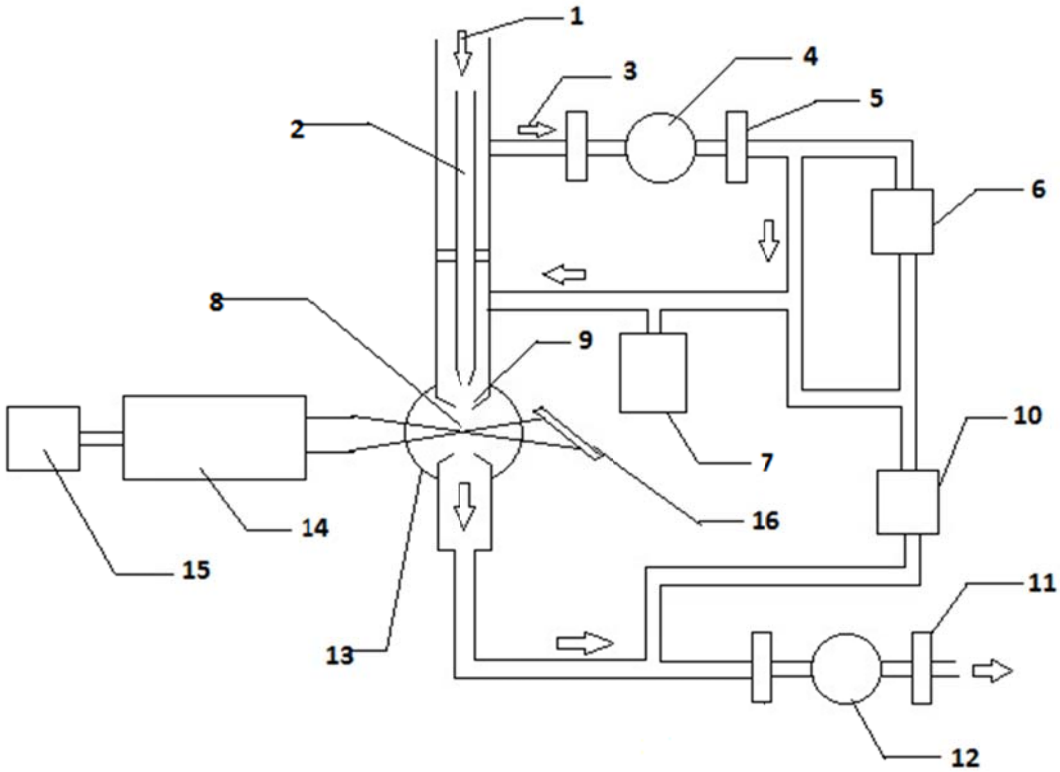
1. Aerosol Outlet
2. Cyclone
3. Elutriator
4. Direction of Aerosol Flow (Upward)
5. Bead Chain
6. Cover of Powder Reservoir
7. Center Shaft (Power supply to the chain)
8. Rake Rods
9. Coal Powder in Powder Reservoir
10. Direction of flow of the bead chain (Clockwise)
11. Air Plenum Chamber
12. Inlet for air supply
13. Filter
14. Fluidized Bed Chamber

Figure 3.3 Schematic Diagram of the Fluidized Bed Aerosol Generator

3.1.2.2 Aerodynamic Particle Sizer

A TSI model 3321 Aerodynamic Particle Sizer Spectrometer or APS was used in this research to determine the concentration of coal particles in the aerosol mixture. Earlier studies were done for aerosol particle analysis using the TSI Aerodynamic Particle Sizer by Chen and Crow (1986), Chen, Cheng et al. (1989) and Ball and Mitchell (1990). These earlier studies were performed with APS model 3300 for measurement of airborne solid particle density and sampling methods analysis. Tests regarding the concentration measurement and counting efficiency was done by Armendariz and Leith (2002) for APS 3320 model and Peters and Leith (2003) for APS 3321 model. These studies have shown that the APS 3321 model (which has been used for this research) is more accurate in matters of counting efficiency of solid aerosols. This result has been supported by Volckens and Peters (2005) who measured 100% counting efficiency for solid particles. Similar studies has also been done by Maynard, Kenny et al. (1999) related to development of system for better sampling and counting of polydisperse aerosols.

A schematic diagram in Figure 3.4 shows the flow of the aerosol inside the instrument and the process by which the concentration and diameters are determined. The APS determines particles within diameters ranging from <0.5 µm to 20 µm. At a concentration higher than 1200 #/c.c., the APS gives a warning light indicating that the aerosol input line to the APS should be disconnected immediately for the safety of the machine. As shown in Figure 3.4, the aerosol enters the instrument at a flow rate of 1 liters/ min and a sheath flow of 4 liters/ min. The sheath flow is filtered and a sheath flow pump is used to control the volumetric flow rate of the sheath flow. After passing through an orifice which measures the pressure drop of this flow, the pressure is compensated and the sheath flow is rejoined with the sample flow at the accelerating orifice nozzle. The purpose of this process of separating the sheath flow from the sample flow and later rejoining it to the sample flow is to keep the sample particles in the center of the flow. The sample particles contain small as well as large particle. The smaller particles accelerate and have a higher velocity than the larger particles. In the optical chamber, the particles scatter the light focused by two laser beams. Once the particle scatters the laser beam, the side scattered light gets collected by an elliptical mirror which focusses the light onto an avalanche photodetector (APD) which converts the light pulses to electrical pulses. Due to the two overlapping laser beams, each particle generates a two crested signal where the peak-to-peak time of flight measured in a resolution of 4 nanoseconds gives the information of the aerodynamic particle sizing. The aerodynamic diameter of the particle is determined using Stokes law from its velocity considering the particle to be a complete sphere having unit density. The particles then exit the optical chamber and are filtered before they leave the instrument. The output of the APS can be obtained both by the digital screen present on the APS and by connecting the APS to a computer and using the associated software. Before every test, the scheduling time or the time during which the sample inlet would be analyzed by the APS is set. The numbers generated by this instrument combined with the electrical charge data generated by the Aerosol Electrometer have been used to calculate the charge per particle of coal over a wide range of flow rates of the FBAG and the motor speed.



1. Aerosol Inlet
2. Sample Flow (1 L/min)
3. Sheath Flow (4 L/min)
4. Sheath Flow Pump
5. Filter for Sheath Flow
6. Sheath-Flow Pressure Transducer
7. Absolute Pressure Transducer
8. Detection Area
9. Accelerating Orifice Nozzle
10. Total-Flow Pressure Transducer
11. Filter for Outlet Flow
12. Total Flow Pump
13. Elliptical Mirror
14. Beam Shaping Optics
15. Laser Beam Source
16. Beam Dump

Figure 3.4 Schematic Diagram of aerosol flow inside an APS

3.1.2.3 Aerosol Electrometer

A TSI model 3068B Aerosol Electrometer was used in this research to determine the charge of the aerosol that was sampled by this instrument. Previously charge measurement of aerosol particles has been done by J-Fatokun, Morawska et al. (2008) using the TSI Aerosol Electrometer. The rate at which the aerosol enters the instrument can be varied from 0.3 liter per minute to 10 liters per minute. A vacuum pump needs to be connected to the instrument to maintain positive pressure throughout the process. There is a control panel in front of the instrument which is used to preset the flow of the aerosol sample into the instrument. Since the APS measured aerosol samples at 1 liter per minute, this instrument was also set at 1 liter per minute for all experiments performed in this research. The following figure describes a schematic of the operating principle of the instrument. A microprocessor controlled built-in thermal flowmeter and proportional valve maintains the aerosol sample flow rate. The aerosol charged particles are collected by an electrically-isolated high efficiency filter that acts as a Faraday cup. Upon collection of the charged particles by the Faraday cup, it gains a certain amount of charge by collecting charges on its metal surface and thereby producing an electric current from which an electrometer measures the current in Femto Amperes (fA). When the instrument showed an abnormally high (positive) or low (negative) at normal room conditions, the zero offset of the instrument was reset from the front control panel of the instrument. The Aerosol Electrometer was connected to the computer and the outputs were obtained using the Aerosol Instrument Manager. In most cases the curve obtained was unsteady for shorter time spans. Shorter time spans were primarily chosen to avoid the instrument getting exposed to too much aerosol and avoid risk of damaging the instrument. Gradually the time span of sampling was increased to get a better curve and lesser standard deviation. As explained before the current data of the Aerosol Electrometer was used along with the data of the APS to calculate the charge per particle of the coal particles.

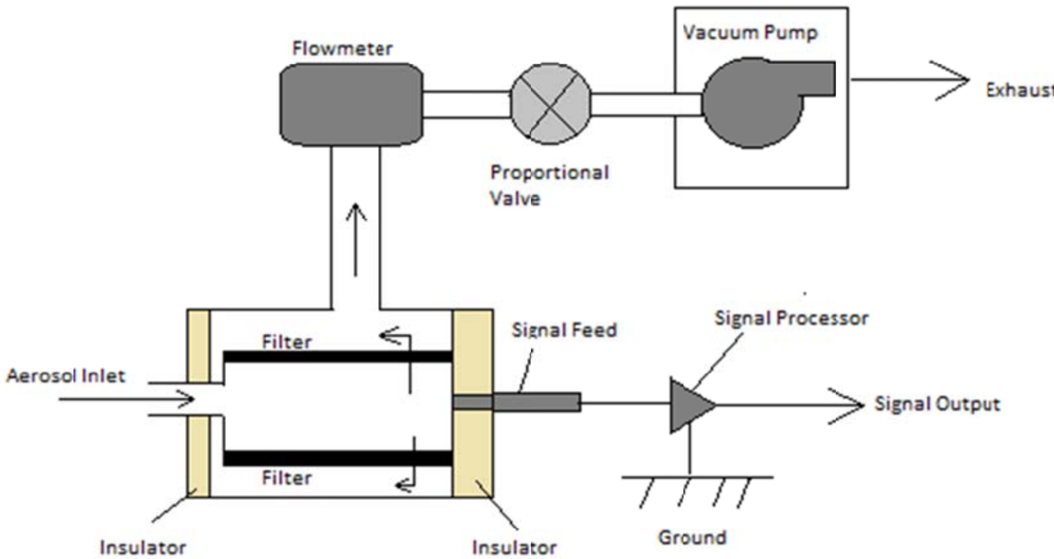


Figure 3.5- Aerosol Electrometer 3068B - Schematic Diagram

3.2 Study of Polydisperse Water Drop Distribution

3.2.1 Experimental Set up

Deionized water was used in the research to capture the coal particles. A Sonaer Ultrasonic Atomizer Nozzle was used to generate water drops for this research. A Wide Spray Nozzle operating at a frequency of 40 kHz was used. This instrument required a constant steady supply of water at its inlet. A maximum of 50 ml/ min of water flow rate could be used with this instrument. Although under experimental conditions a maximum of 10 ml/ min was possible due to design restrictions. The water was supplied to the Atomizer using a syringe pump. The syringe pump was used to vary the flow rate of the water from 1 ml/ min to 10 ml/ min. The atomizer was vertically placed on the top of a vertical chamber and used later to capture coal particles generated by the FBAG as shown in the Figure 3.7. The chamber was made leak proof at all places. One set of experiments was performed by varying the flow rate of the water from 2 to 30 ml/min in presence of counter current air flow from the FBAG and collecting the water at the bottom of the column to analyze the volume of water blown away by the upward air flow.

3.2.2 Descriptions of instruments used

3.2.2.1 Sonaer Ultrasonic Atomizer

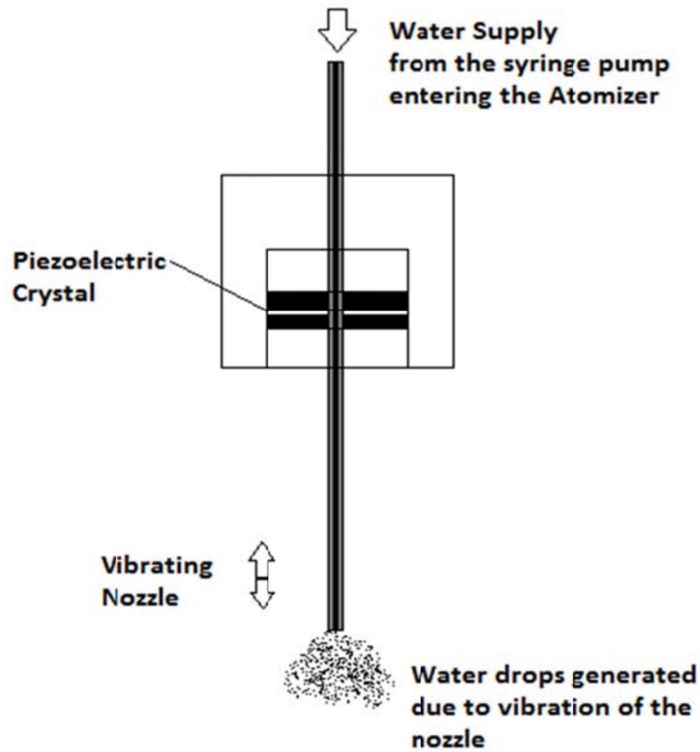


Figure 3.6 Schematic Diagram of Atomizer spraying DI water

The principle of the Atomizer nozzle can be explained with the Figure 3.6. The water enters the instrument from the top and reaches the tip of nozzle. There is a piezoelectric crystal inside the instrument to which the power supply is attached. The crystal converts the electric signal to mechanical vibrations which in turn vibrates the tip of the nozzle creating standing waves. Due to this the water upon reaching the tip nozzle gets broken into drops. The frequency of vibration used for this experiment was 40 kHz. The advantages of this instrument is that it is very easy to operate and can be used in both horizontal and vertical positions. The power of the Atomizer can be varied from 0 to 100%. For the majority of the successful experiments, it was run at 50% power.

3.3 System for coal dust capture using water droplets

3.3.1 Experimental setup

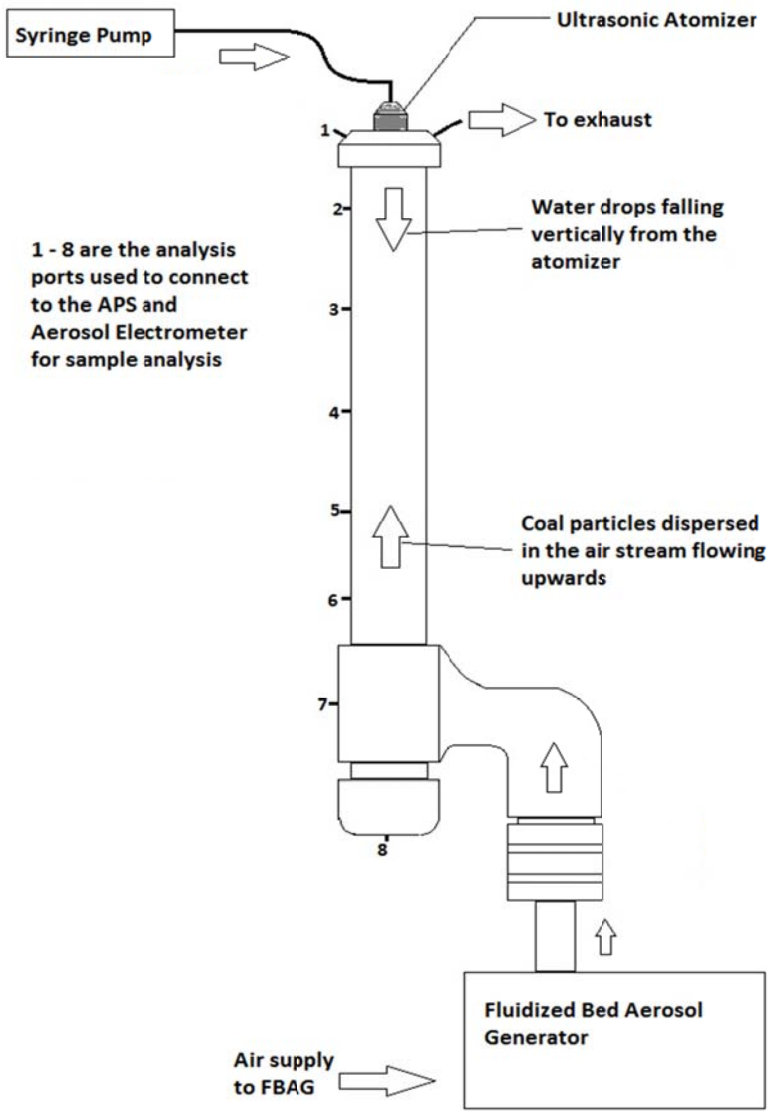


Figure 3.7 -Schematic Diagram of scrubbing column for coal particle capture by water spray showing coal particles dispersed in the air by the FBAG and water drops sprayed by the Ultrasonic Atomizer

Figure 3.7 gives a schematic idea of the experimental set up used for the study of capture of coal particles using water drops. Similar to the designs used for the previous two types of experiments, this set up uses combinations of the previous designs. The principle behind the experiment was to create a counter flow of the water drops and the air containing the coal particles inside a sealed chamber. For this purpose the air stream containing coal particles generated by the FBAG was allowed to flow upward from the bottom, while water drops generated by the atomizer was allowed to fall downward from the top of the chamber. The dimensions of the design were made so that certain essential parameters were optimized and the instrument allowed both the streams to reach steady state. The main column as shown in Figure 3.7 measured 36 inches in height and 3 inches in diameter, which is the point of generations of the water drops to the point of collection of the water. The water was supplied to the atomizer at the top by the syringe pump. The rate of flow of water was varied from 1 ml/ min to 10 ml/min. The air was flowed out of the chamber through an exhaust on the top. The whole set up had ports at regular intervals numbered 1 to 8. These ports were used to take in samples from chamber and analyze them using the APS. The readings of the APS were typically done at two instances during the experiment. First was when only the FBAG was turned on and the coal particle concentration was allowed to reach a steady state. This process typical took about 30 minutes. During this period the port number 7 was used to analyze. In some cases port number 8 was also used which had an inner steel tube that went till the position of port 7 but at the center of the column. This was performed to see the difference in the concentration at the wall and the center. This was nearly found to be same in value, so the port number 8 was not used much. The ports 1, 2, 3, 4, 5 and 6 were also used to test samples with the APS. This was done to see the variation of the concentration of the coal particles with the height of the column. For maximum numbers of conditions not many variations were found from the values found at ports 7 and 8. After the coal concentration became steady inside the chamber the water from the Atomizer was allowed to fall down into the chamber. This was allowed to go on for a few minutes to get the process into steady state. Then at regular intervals of 1 minute, 2 minutes or more, samples were tested from only port 1 which is on the top. These APS readings gave values and distributions of concentrations of the coal particles that came out of the chamber. These coal particles were not captured by the water drops. The readings which were taken when both the FBAG and Atomizer were operating, were never taken from any other ports apart from 1 or 2. This was done so that the point of detection was after the point of generation of water drops.

3.4 Summary

The four major instruments used in this research, APS, FBAG, Aerosol Electrometer and Ultrasonic Atomizer have been discussed in detail in this chapter along with the experimental setup used in each kind of experiment. The description of the experimental setups used, provide detailed understanding of the experimental conditions and the variable parameters. Upon variation of the parameters such as air flow rate, motor speed and water flow rate, the overall scrubbing efficiency and the capture efficiency of a single droplet has been measured and also compared with the theoretical solutions obtained earlier.

Chapter 4

Data Analysis

Experiments were performed for the characterization of coal dust, determination of water drop distribution generated by the ultrasonic atomizer, determination of capture efficiency of a single drop and overall scrubber efficiency. This chapter discusses the procedure for calculating the single drop efficiency from the raw data generated by experimentation.

4.1 Characterization of coal dust

Coal particles dispersed in the air stream by the Fluidized Bed Aerosol Generator (FBAG) were analyzed for presence of electrical charge using the experimental system as shown in Figure 3.1. A fraction of the air stream was allowed to pass through the Aerodynamic Particle Sizer (APS) and Aerosol Electrometer. The number density and the current generated due to collection of the particles was used to calculate the charge per particle using equation below,

$$q = \frac{I}{N_p \times e \times Q_g} \tag{4.1}$$

where q is the charge (elementary unit of charge) per particle, I is the current in Amperes (calculated from the Aerosol Electrometer reading in Femto Amps), N_p is the number concentration of particles (APS reading in particles per cm^3), e is the elementary unit of charge (1.602 X 10^{-19} Coulombs) and Q_g is the volumetric flow rate (Liters/min) of the air intake in the APS/ Aerosol Electrometer at 1 Liter/min. The number concentration of particles was varied by changing the air flow rate and the motor speed of the FBAG. For an air flow of 5 liters/min at 50% of maximum motor speed, the N_p is 881.2 particles per cm^3 and Aerosol electrometer reading is 333.8 fA. Hence the charge per particle calculated from equation (4.1) is 142 e (elementary units of charge).

The mass concentration of the coal particles dispersed in the air stream by the FBAG was determined using an experimental system as described in Figure 3.2. The air stream containing dispersed coal particles was passed through a sealed chamber having filter papers in the path of the flow. The air stream was passed through the chamber for a definite period of time as a result of which, the coal particles were collected in the filter papers. By the method of weighing the filter papers before and after the coal deposition, the mass concentration of the coal dust dispersed in the air stream was calculated using the equation below,

$$C_m = \frac{M}{Q_g \times t} \tag{4.2}$$

where M is mass of coal collected by the filter papers in mg, C_m is the mass concentration in mg/m^3, Q_g is the air flow rate in m^3/min (calculated from FBAG rotameter reading in liters/min) and t is the time of collection in minutes. For an air flow rate of 12 liters/min and time period of 30 minutes, the mass collected is 15 mg when the motor speed was 40% of the maximum value. Hence the mass concentration calculated from equation (4.2) is 41.94 mg/m^3.

4.2 Water droplet distribution

Water spray was generated using an ultrasonic atomizer nozzle. The ultrasonic atomizer nozzle operating at 40 kHz generates water drops of size varying from 0.5 to 90 µm as per the manufacturer specifications. It is assumed that the trajectory of the free falling water drop is vertical without any curvature. The time taken by a drop to reach the terminal velocity is a function of the drop diameter and is estimated to vary from 10^{-5} to 10^{-2} seconds. The terminal velocity of a free falling water drop is a function of drop diameter (D_i) and the Reynolds number (Re). For droplet diameter less than 50 µm where the Re < 0.1, Stokes Law can be used to calculate the terminal velocity (V_i) using the following equations.

$$V_i = \frac{\rho_d g {D_i}^2 C_c}{18\mu} \tag{4.3}$$

Where the Cunningham correction factor (C_c) can be given as,

$$C_c = 1 + \frac{0.13735}{D_i}[1.257 + 0.4\exp(-8.0087\ D_i)] \tag{4.4}$$

Drop diameter (D_i) is in μm, the Reynolds number is given as $Re = \frac{\rho V_i D_i}{\mu}$, ρ and μ are the density and viscosity of air respectively and g is the constant of acceleration due to gravity. For diameters greater than 50 μm and less than 100 μm and Re < 2, terminal velocity (V_i) is determined using the following equations,

$$ {V_i}^2 = \frac{4D_i\rho_d g}{3C_D(Re)\rho} \tag{4.5}$$

Where the drag coefficient $C_D(Re)$ is a function of Re given as,

$$C_D(Re) = \frac{24}{Re}\left[1 + \frac{3}{16}Re + \frac{9}{160}Re^2\ln(2Re)\right] \tag{4.6}$$

and ρ_d is the density of the droplet. Modifying equation 4.5 for calculating $Re^2 C_D(Re)$ we get the following,

$$Re^2 C_D(Re) = \frac{4{D_i}^3\rho\rho_d g}{3\mu^2} \tag{4.7}$$

Combining equations 4.6 and 4.7, we get the following,

$$Re^2 C_D(Re) = 24\left[Re + \frac{3}{16}Re^2 + \frac{9}{160}Re^3\ln(2Re)\right] \tag{4.8}$$

The numerical technique $x_{n+1} = f(x_n)$ is used on equation 4.8 for calculating Re taking Re =1 as the initial guess and iterating to converge to a solution such that Re < 2. Solution of Re determines the value of terminal velocity (V_i) for the drop diameter (D_i). The experimental conditions are pressure = 1 atm, temperature = 298 K, μ = 1.81 x 10^{-5} kg/m.s, ρ =1.2 kg/m^3 and ρ_d (water) = 1000 kg/m^3.

The size distribution of drops generated by the ultrasonic atomizer with the corresponding percentage volumetric flow rate for every diameter given by manufacturer specification data sheet is shown in Figure 4.1.

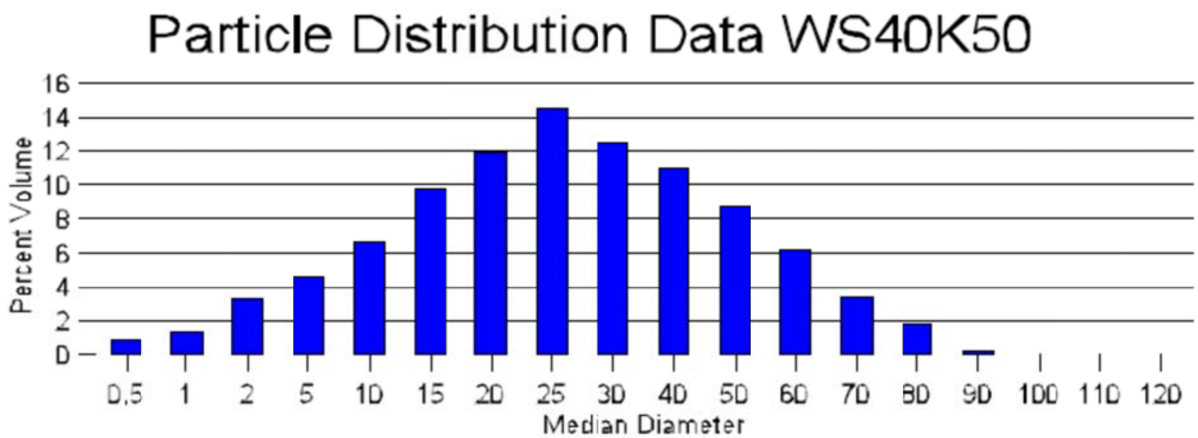


Figure 4.1- Water drop distribution from 40 kHz nozzle Sonozap Atomizer

The terminal velocity is calculated for every drop diameter shown in Figure 4.1 using equations 4.3 to 4.8 and is presented in Figure 4.2.

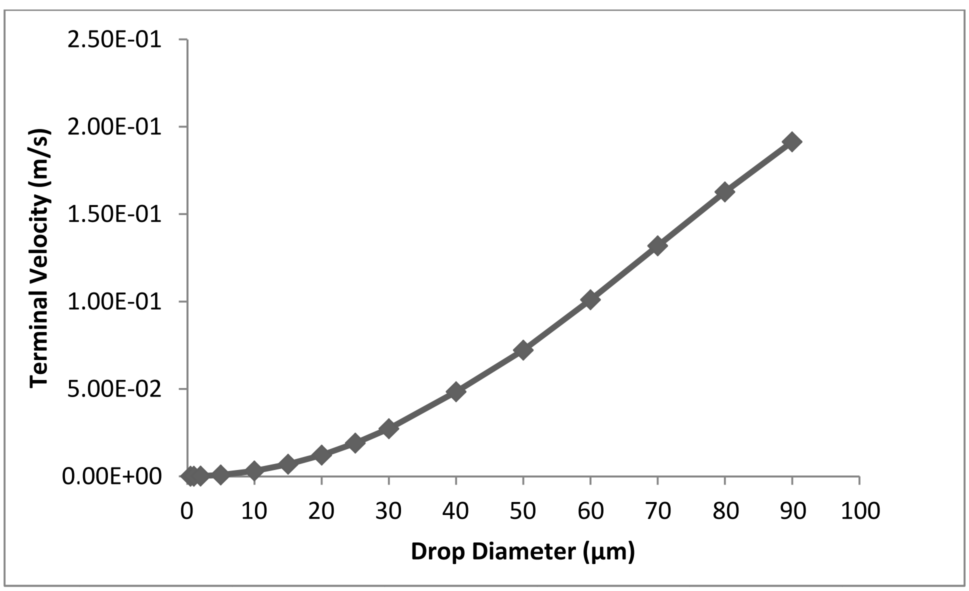


Figure 4.2 – Terminal Velocity of water drops as a function of drop diameter.

However, all the drops generated by the atomizer did not fall freely along the length of scrubber and encounter coal particles. A certain percentage of drops were carried away by the upward air flow and lost to the chamber wall. To quantify the percentage of volume lost in the scrubbing process, a set of experiments were carried out where water drops from the atomizer were allowed to fall in the scrubbing column and the water was collected at the bottom of the tower. This was done however in the presence of a countercurrent air flow from the FBAG (without any coal particles) so that the effect of upward force acting on the free falling water drops would be dominant. The water flow rate was 2 ml/min for 30 minutes such that without any loss the volume collected at the bottom of the column would be 60 ml. The air flow rate was varied from 2 liters/min to 30 liters/min as shown in Table 4.1. The percentage of volume collected has been calculated, where 100% (60 ml) would be the ideal volume collected without any air flow.

Table 4.1

Results of the water collection experiment in the scrubbing column in presence of upward air flow, with water flow rate = 2 ml/min and time of collection = 30 minutes.

Air Flow Rate	Run 1		Run2	
Q_g (Liters/min)	Volume Collected (ml)	% Volume	Volume Collected (ml)	% Volume
2	53	88.33	53	88.33
4	53	88.33	53	88.33
10	42	70	41	68.33
15	37	61.67	36	60
20	33	55	33	55
25	29	48.33	28	46.67
30	15	25	15	25

Figure 4.2 shows that the terminal velocity of a drop decreases with the decrease in diameter. Hence it has been assumed that the loss in the water volume collected is primarily due to the drops having terminal velocity lower than the upward velocity of

the air, being carried away by the air. Hence it is necessary to determine the percentage loss occurring under experimental conditions of air flow which are 4, 5, 7, 8, 9 and 10 liters/min. Using the data from Table 4.1, the percentage loses in volume collected have been interpolated using the following linear trendline equation,

$$y = -3.333 + 101.67x \tag{4.9}$$

where x is the air flow rate and y is the volume percentage. The R^2 value for the trendline is 1 which minimizes the possibility of errors for interpolation. Table 4.2 shows the interpolation results, where the percentage volume collected corresponding to the upward air flow rate has been interpolated.

Table 4.2
Interpolation results of Air Flow Rate and the corresponding percentage volume collected

Q_g (Liters/min)	% Volume
4	88.335
5	85.002
7	78.336
8	75.003
9	71.67
10	68.337

In order to determine the size distribution of the water drops corresponding to the volume percentage collected, the manufacturer specification data sheet of Figure 4.1 has been modified to Figure 4.3 which presents the cumulative volume percentage variation with the corresponding drop diameter in µm.

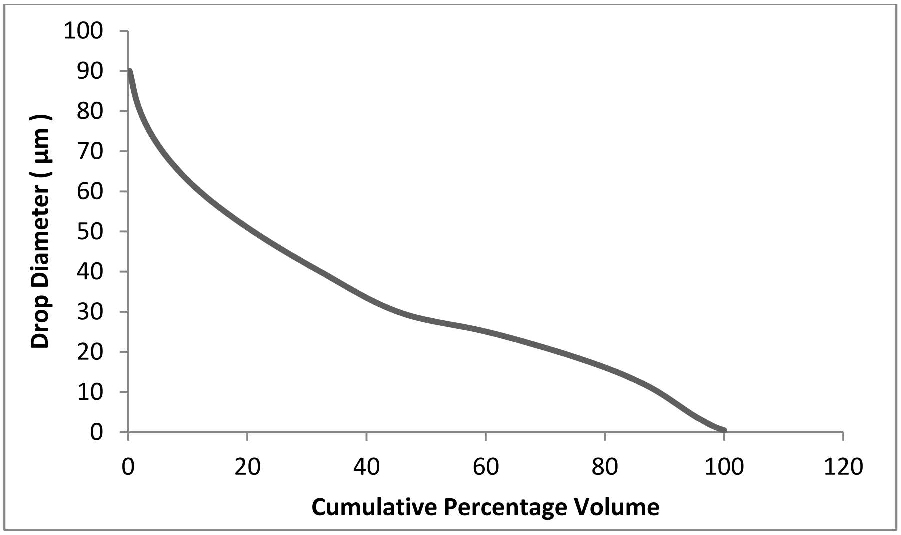


Figure 4.3 – Cumulative volume percentage variation with the drop diameter (µm)

The results of Table 4.2 and Figure 4.3 is used to determine the minimum drop diameter which would be present in the scrubber column for coal particle capture, for a particular air flow rate. For example, for an air flow rate of 5 Liters/min, the volume percentage collected is 85% as per Table 4.2. This interpolation result was used in Figure 4.3 to get the minimum drop diameter as 15 µm. Thus for an air flow rate of 5 Liters/min, the drop size distribution would be from 15 to 90 µm which would be involved in the scrubbing process of coal particle capture. This method has been used to generate Table 4.3 which shows the minimum drop diameter present in the scrubbing process for a particular air flow rate.

Table 4.3
Minimum drop diameter corresponding to the upward air flow rate

Q (Liters/min)	Minimum diameter (µm)
4	15
5	15
7	20
8	20
9	25
10	25

Another method is used for determination of drop size distribution for a particular air flow rate. On the basis of the assumption that water drops having terminal velocity lower than the upward air velocity are carried away by the air, the minimum drop diameter having a terminal velocity (V_i) higher than the upward air velocity (V_g) corresponding to each air flow rate is determined. The results of this calculation are shown in the Table 4.4.

Table 4.4
Determination of minimum drop diameter using the criteria-
Terminal velocity of smallest drop (V_i) > Upward Air Velocity (V_g)

Air Flow Rate (Liter/min)	Corresponding Upward Air Velocity V_g (m/s)		Minimum Diameter (μm)	Corresponding Terminal Velocity V_i (m/s)
4	1.46E-02		25	1.89E-02
5	1.83E-02		25	1.89E-02
7	2.56E-02		30	2.73E-02
8	2.92E-02		40	4.84E-02
9	3.29E-02		40	4.84E-02
10	3.65E-02		40	4.84E-02

The results of Table 4.3 and Table 4.4 give two separate drop size distribution based on the two methods which are used to calculate the capture efficiency of a single water drop.

4.3 Capture Efficiency Calculation

Experiments were performed to capture the coal particles dispersed in the air stream by the FBAG using the water spray generated by the ultrasonic atomizer. Capture efficiency (η) of a single water drop falling at its terminal velocity is defined as the ratio of the number of coal particles captured by the drop to the number of coal particles encountered by the drop in its path as shown below.

$$\eta = \frac{Number\ of\ coal\ particles\ captured\ by\ the\ drop}{Number\ of\ coal\ particles\ encountered\ by\ the\ drop}$$

Capture efficiency is 1 when all the coal particles encountered by the water drop are captured by it. A schematic diagram of coal particle capture process has been described by the following figure.

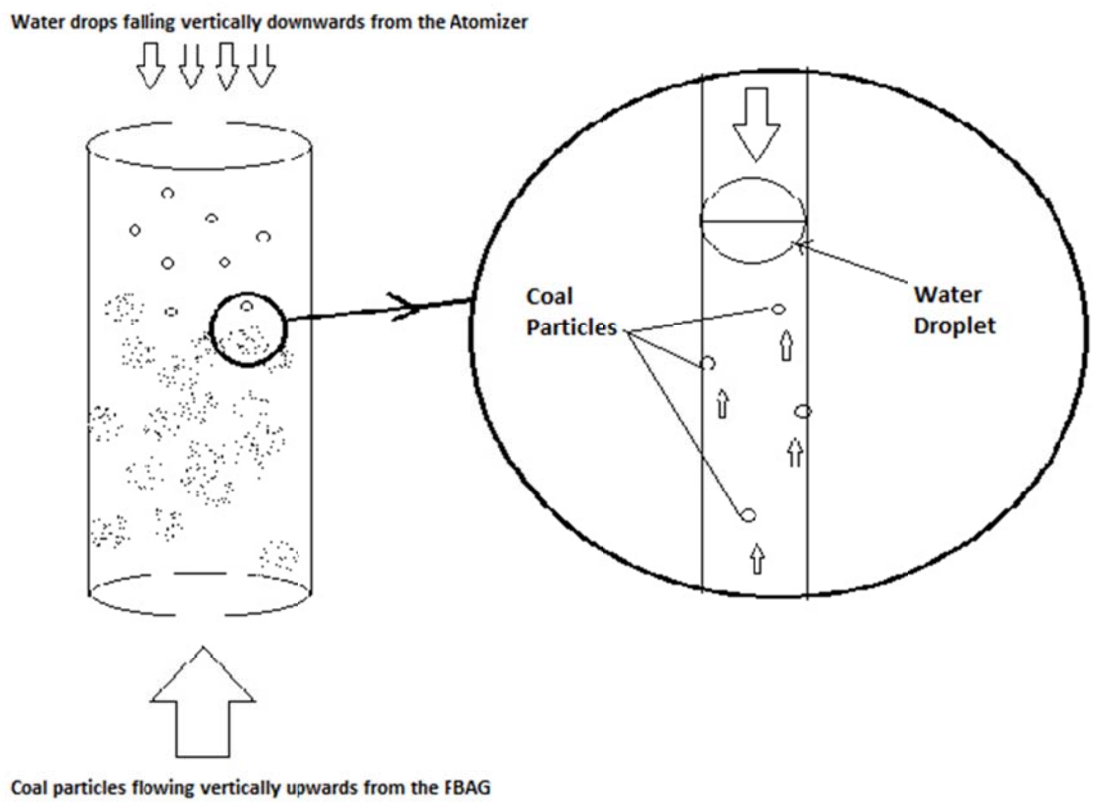


Figure 4.4- Schematic diagram of coal particle capture by falling water drops

In order to experimentally calculate the capture efficiency of single drop a mathematical model has been developed. Lim, Lee et al. (2006) performed a mass balance for particle capture in a scrubber column using water spray and developed the following equation.

$$\frac{N_p(L)}{N_p(0)} = e^{\left\{-\frac{3}{2}\eta \frac{V_t W L}{V Q_g D}\right\}} \tag{4.10}$$

where $N_p(0)$ and $N_p(L)$ are the number particle concentration at the column inlet and column outlet respectively, η is the capture efficiency of a single water drop, V is the terminal velocity of the water drop, V_t ($V_t = V_g + V$) is the relative velocity of the water drop with respect to the upward air velocity, V_g is the upward air velocity, W is the volumetric flow rate of the water spray, Q_g is the volumetric flow rate of the air and L is the height of the column. For the experimental system used in this research, $N_p(0)$ and $N_p(L)$ are determined from the APS reading at the respective positions on the column. The length (L) of the column is 0.635 m. Q_g and W are the variable parameters which are set by the user. The upward air velocity (V_g) is determined by the following equation

$$V_g = \frac{Q_g}{A_c} \tag{4.11}$$

where the cross-section area of the scrubber column (A_c) is 4.56 x 10^{-3} m^2. The capture efficiency of a single water drop is a function of the water drop diameter (D) and the particle diameter (d_p).

$$\eta = \eta\left(D, d_p\right) \tag{4.12}$$

The particle diameter (d_p) is assumed to be constant for this study. According to the APS results, the average particle diameter is assumed to be 0.9 µm which has been used for theoretically calculating the capture efficiency. The drop diameter (D) was however not constant and had a size distribution as shown in Figures 4.1 and 4.2. Lim, Lee et al. (2006) developed the model assuming the water spray generated monodisperse water drops of uniform diameter and the capture efficiency (η) is the same for every drop diameter (D). However in this research the water spray being polydisperse having distribution of drop diameter (D_i) from 0.5 to 90 µm, equation (4.10) has been modified as,

$$\ln\frac{N_p(L)}{N_p(0)} = \left[-\frac{3}{2}\eta\frac{L}{Q_g}Y\right] \qquad where\ Y = \sum\left(\frac{V_{t_i}W_i}{D_iV_i}\right) \tag{4.13}$$

Solving for η, $$\eta = \left[-\frac{2}{3}\frac{Q_g}{LY}\right]\ln\frac{N_p(L)}{N_p(0)} \tag{4.14}$$

For every drop diameter (D_i), the corresponding terminal velocity (V_i), relative velocity (V_{ti}) and water flow rate (W_i) can be determined for every D_i from Figure 4.2 and equation (4.11). For a polydisperse drop distribution, every drop diameter D_i would have corresponding capture efficiency (η_i). It was assumed that drops of all sizes have the same capture efficiency, which is $\eta_i = \eta$. Equations (4.13) and (4.14) determine the average capture efficiency for a polydisperse drop distribution.

A series of experiments were performed by varying the air flow rate (Q_g) and water flow rate (W) in the scrubbing column and the capture efficiency was calculated from the experimental data using equation (4.12). For every case of air flow rate (Q_g), there are two methods of determining the drop size distribution. In the first method, the results of the water collection experiment presented in Tables 4.1 and 4.2; were used to determine the minimum diameter for every air flow rate and the corresponding drop size distribution. The capture efficiency calculated was denoted as η_1. In the second method, the minimum diameter is determined by the criteria $V_g < V_i$, where the minimum drop diameter was such that its terminal velocity is greater than the upward air velocity. For every air flow rate (Q_g), the upward air velocity (V_g) was compared with the terminal velocities (V_i) and the minimum drop diameter corresponding to the air flow rate thus determined was presented in Table 4.4. The capture efficiency thus calculated using this method was denoted as η_2.

The overall scrubber efficiency can be determined by the following equation,

$$\eta_{scrubber} = 1 - \frac{N_p(L)}{N_p(0)} \tag{4.15}$$

Sample calculation of scrubber efficiency ($\eta_{scrubber}$), capture efficiency determined from first method (η_1) and second method (η_2) -

For a case of Q_g= 10 liters/min, W = 3 ml/min, L = 0.635 m and V_g = 0.0365 m/s, there are two methods for calculating the capture efficiency for a single drop, η_1 and η_2. The inlet particle number concentration $N_p(0)$ is 509 particles / cm^3 and outlet particle number concentration $N_p(L)$ is 189 particles / cm^3. For the first method, Table 4.3 indicates that the minimum drop diameter is 25 µm for an air flow rate of 10 Liters/min. Using that as a basis, the values of W_i, V_{ti} and Y_i for the corresponding D_i can be determined as shown in the Table 4.5. The capture efficiency (η_1) thus calculated using equation (4.14) is 9.18 %.

Table 4.5

Drop distribution and corresponding parameters determined using the first method

D_i (µm)	% Volume	V_i (m/s)	V_{ti} (m/s)	W_i (m^3/s)	Y_i
25	15	1.89E-02	5.55E-02	7.50E-09	8.79E-04
30	13	2.73E-02	6.38E-02	6.50E-09	5.07E-04
40	11.25	4.84E-02	8.49E-02	5.63E-09	2.47E-04
50	9	7.22E-02	1.09E-01	4.50E-09	1.36E-04
60	6.25	1.01E-01	1.38E-01	3.13E-09	7.09E-05
70	3.75	1.32E-01	1.68E-01	1.88E-09	3.42E-05
80	1.75	1.63E-01	1.99E-01	8.75E-10	1.34E-05
90	0.25	1.91E-01	2.28E-01	1.25E-10	1.65E-06

The second method is a theoretical approach where the smallest drop diameter present in the coal dust capture is determined by the criteria $V_i > V_g$. In this case, the smallest drop diameter (from Table 4.4) is 40 µm. The values of W_i, V_{ti} and Y_i for the corresponding D_i can be determined similarly as shown in Table 4.6. The capture efficiency (η_2) thus calculated is 34.49 %.

Table 4.6

Drop distribution and corresponding parameters determined using the second method

D_i (µm)	% Volume	V_i (m/s)	V_{ti} (m/s)	W_i (m^3/s)	Y_i
40	11.25	4.84E-02	8.49E-02	5.63E-09	2.47E-04
50	9	7.22E-02	1.09E-01	4.50E-09	1.36E-04
60	6.25	1.01E-01	1.38E-01	3.13E-09	7.09E-05
70	3.75	1.32E-01	1.68E-01	1.88E-09	3.42E-05
80	1.75	1.63E-01	1.99E-01	8.75E-10	1.34E-05
90	0.25	1.91E-01	2.28E-01	1.25E-10	1.65E-06

From equation (4.15), the scrubber efficiency is $\eta_{scrubber} = 62.87\%$. Depending upon the experimental conditions such as air flow rate (Q_g) and water flow rate (*W*), the captures efficiencies as well as the scrubber efficiency varied. The air flow rate was varied from 4 to 10 liters/min and the water flow rate was varied from 2 to 10 ml/min.

4.4 Comparison of calculated capture efficiency with theoretical solutions

The calculated capture efficiencies using the two approaches were compared with the theoretical models discussed in Chapter 2. For comparison with Slinn (1983), equation (2.4) was used where the mean free path (λ) was taken as 68 nm and the mean particle diameter (d_p) was taken as 0.9 µm. Equation (2.4) can be written as the following such that the effective capture efficiency due to Brownian diffusion is only a function of the drop diameter (*D*).

$$\eta_{diff}\,(D) = \frac{1}{Re\,Sc}\left[1 + 0.4Re^{\frac{1}{2}}Sc^{\frac{1}{3}} + 0.16Re^{\frac{1}{2}}Sc^{\frac{1}{2}}\right] \qquad (4.16)\,,$$

$$Re = \frac{DV\rho}{2\mu}, \quad Sc = \frac{\mu}{\rho D_{diff}}, \quad D_{diff} = \frac{k_b T C_c}{3\pi\mu d_p},$$

and $$C_c = 1 + 2.493\frac{\lambda}{d_p} + 0.84\frac{\lambda}{d_p}\exp\left(-0.435\frac{d_p}{\lambda}\right).$$

Under experimental conditions, the drop diameter varied from 2 to 90 µm. Hence the variation of capture efficiency (η_{diff}) with drop diameter has been studied as predicted by equation (4.16). The comparison with the capture efficiency predicted by H. T. Kim (2001) was done with reference to three separate set of equations for Brownian diffusion, interception and impaction. The capture efficiency due to Brownian diffusion is given by the following equation.

$$\eta_{diff} = 0.7\left\{\frac{4}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{\frac{1}{2}} Pe^{-\frac{1}{2}} + 2\left(\frac{\sqrt{3}\pi}{4Pe}\right)^{\frac{2}{3}}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{\frac{1}{3}}\right\} \tag{4.17}$$

where the Cunningham correction factor (C_C) is

$$C_c = \frac{2.609\sqrt{2\lambda}}{d_p^{\frac{1}{2}}} \quad 0.05\,\mu m < d_p < 1.0\,\mu m \tag{4.18}$$

and α is the volume fraction of drop, σ is the viscosity ratio of water to air,

$$J = 1 - \frac{6}{5}\alpha^{\frac{1}{3}} + \frac{1}{5}\alpha^2, \qquad K = 1 - \frac{9}{5}\alpha^{\frac{1}{3}} + \alpha + \frac{1}{5}\alpha^2$$

$$\text{and } Pe = \frac{DV}{D_{diff}} \text{ (Peclet Number)}$$

Similar to Slinn (1983), the particle diameter (d_p) was taken as 0.9 µm and the mean free path (λ) was taken as 68 nm. The capture efficiency due to interception given by H. T. Kim (2001) was determined by the following equation.

$$\eta_{int} = \left[\frac{(1-\alpha)}{(J+\sigma K)}\frac{1}{D}\right]d_p + \left[\frac{(1-\alpha)}{(J+\sigma K)}\frac{(3\sigma+4)}{2D^2}\right]{d_p}^2 \tag{4.19}$$

The interception mechanism of capture is applicable for this research since it considers particles falling in the zone of one particle radius of the water drop trajectory. It is a valid assumption to consider this effect since the particle sizes are of the order of 0.9 to 1 µm and the drops are of sizes from 2.5 to 90 µm which are one order higher than the particle size. The capture efficiency due to impaction given by H. T. Kim (2001) is as follows.

$$\eta_{imp} = 3.4(Stk)^{\frac{9}{5}} \quad for \quad Stk \leq 0.5 \tag{4.20}$$

and

$$\eta_{imp} = 1 \qquad for \quad Stk > 1 \tag{4.21}$$

where Stokes number is given as, $Stk = \frac{\rho_p {d_p}^2 (V - V_{si})}{18\mu D}$,and V_{si} is the settling velocity of the particle. However, impaction mechanism of particle capture is highly dependent on the Stokes number and is applicable for particles larger than 5 µm with Stk > 1. In this study since the particle size is less than 1 µm, the mechanism of particle capture by impaction is not very dominant. The variation of the capture efficiencies due to the three effects of Brownian diffusion, interception and impaction independently as a function of the water drop diameter using equations (4.17), (4.19) and (4.20) respectively is shown in Figure 4.5. The total capture efficiency due to all the three effects of Brownian diffusion, interception and impaction as predicted by H. T. Kim (2001) can be given as a sum of efficiencies predicted by equations (4.17), (4.19) and (4.20). The variation of the capture efficiency predicted by Slinn (1983) from equation (4.16) and that by H. T. Kim (2001) from equations (4.17), (4.19) and (4.20) as a sum of the three effects of Brownian diffusion, interception and impaction as a function of the water drop diameter in the range of the experimental study has been shown by Figure 4.6.

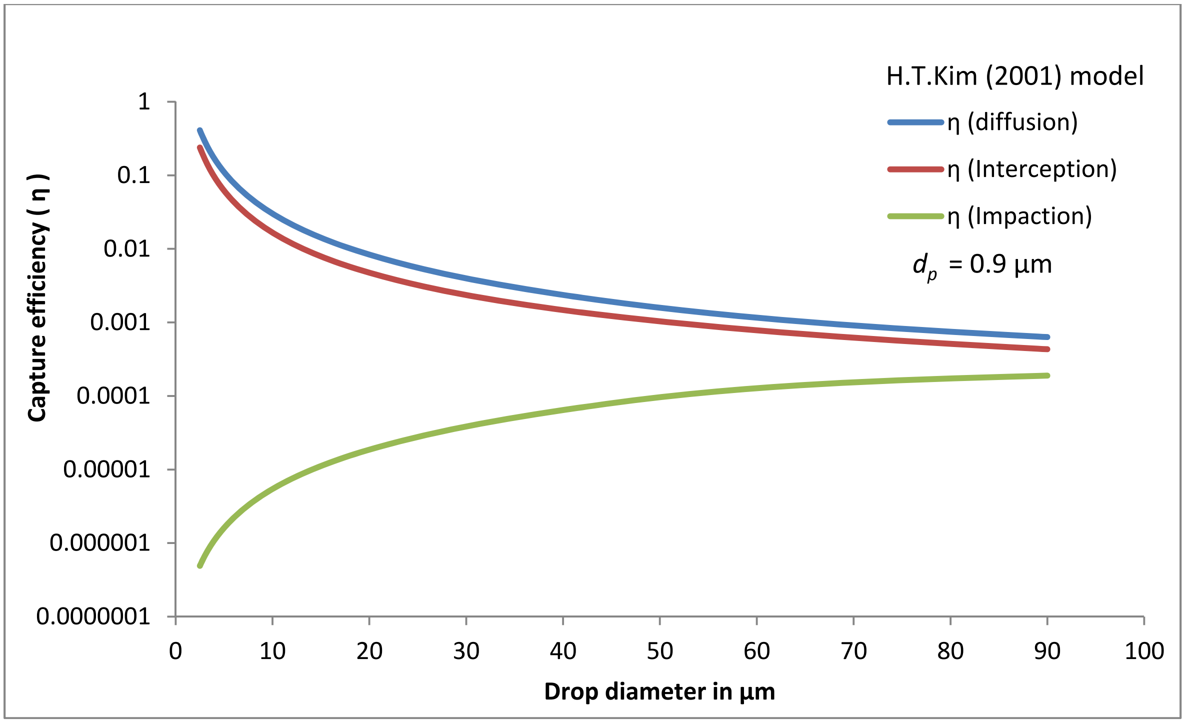


Figure 4.5 – H.T.Kim (2001) prediction of capture efficiencies due to diffusion, interception and impaction respectively as a function of drop diameter.

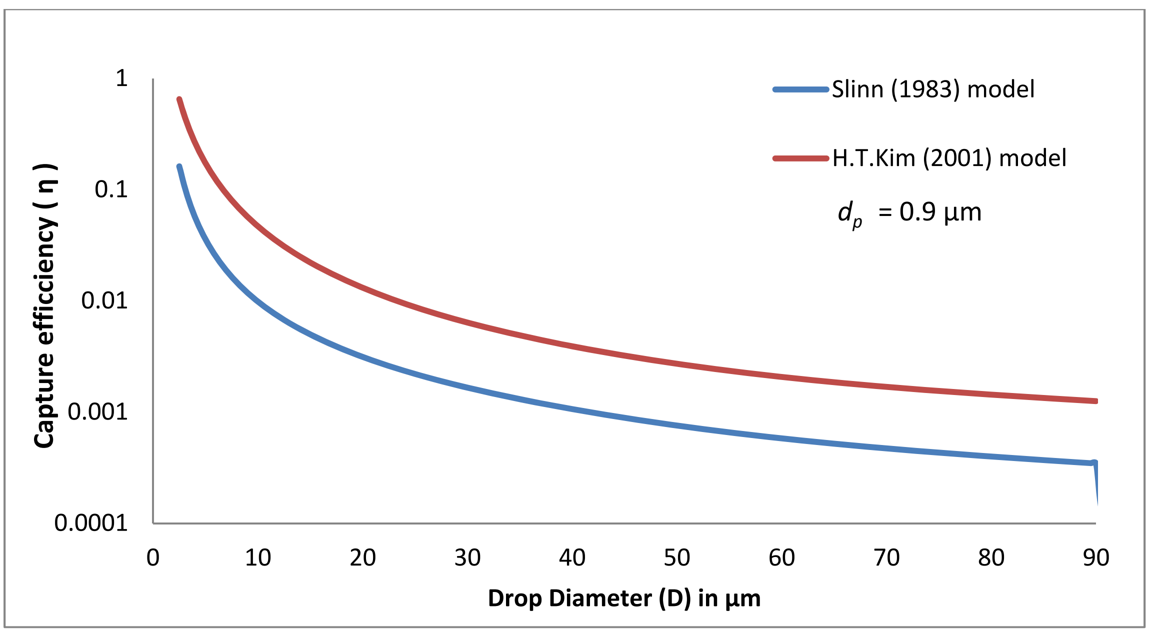


Figure 4.6 Slinn (1983) and H.T.Kim (2001) prediction of Capture Efficiency vs Drop Diameter

An average capture efficiency (η_{avg}) can be calculated for every case of air flow rate and water flow rate using the following equation

$$\eta_{avg} = \frac{\sum \frac{\eta_i V_{t_i} W_i}{V_i D_i}}{\sum \frac{V_{t_i} W_i}{V_i D_i}} \tag{4.22}$$

where η_i is the capture efficiency determined theoretically from equations (4.16), Slinn (1983) and (4.17) to (4.20), H. T. Kim (2001) for the drop distribution having diameter D_i, water flow rate W_i, terminal velocity V_i and relative velocity V_{t_i}. The average capture efficiency calculated from equation (4.22) has been compared with the corresponding experimental capture efficiencies (η_1 & η_2). For instance, for the case of Q_g= 10 liters/min, W = 3 ml/min, L = 0.635 m and V_g = 0.0365 m/s, the calculated $\eta_{avg}(s)$ corresponding to the drop distribution for η_1 and η_2 is shown in the following table.

Table 4.7

Sample comparison of experimentally determined and theoretically determined capture efficiencies.

Experimental		Calcualted Average Capture Efficiency			
Capture Efficiency			η_{avg}		
		Slinn	Slinn	H.T.Kim	H.T.Kim
η_1	η_2	η_1	η_2	η_1	η_2
9.18E-02	3.45E-01	1.69E-03	8.51E-04	7.90E-03	3.60E-03

The physical interpretations of the results of Table 4.8 test the validity of the theoretically derived results as well as the experimental limitations of this research.

Chapter 5

Results and Discussions

Appropriate mathematical models have been used to compare the data generated by experimentation for the purpose of coal dust characterization, water drop size distribution determination and capture efficiency calculation of a single drop and overall scrubber. The results of these studies have been presented in a graphical manner in this chapter along with their interpretations and limitations.

5.1 Characterization of coal dust particles

For detection of the presence of electric charge in the coal particles dispersed by the Fluidized Bed Aerosol Generator (FBAG), experiments were carried out in a cylindrical chamber as shown in Figure 3.1. Previously the presence of electrostatic charges in airborne dust particles have been shown by Marra Jr. and Coury (2000) and Marra Jr, Rodrigues et al. (2009).

The first set of experiments were carried out by keeping the motor speed of the FBAG at 50% of the maximum and varying the air flow rate from 5 to 13 Liters/min. These tests were carried out in two conditions, one in normal atmospheric condition and another in a humidified atmospheric condition (humidified nitrogen gas stream generated by passing the gas through water). Using the Aerodynamic Particle Sizer (APS) and Aerosol Electrometer data, the charge per particle was calculated using equation 4.1. Figure 5.1 shows the results on the charge per particle for the two conditions at various air flow rates. The charge per particle is reported in terms of multiples of elementary charges, $e = 1.602 \times 10^{-19}$ Coulombs.

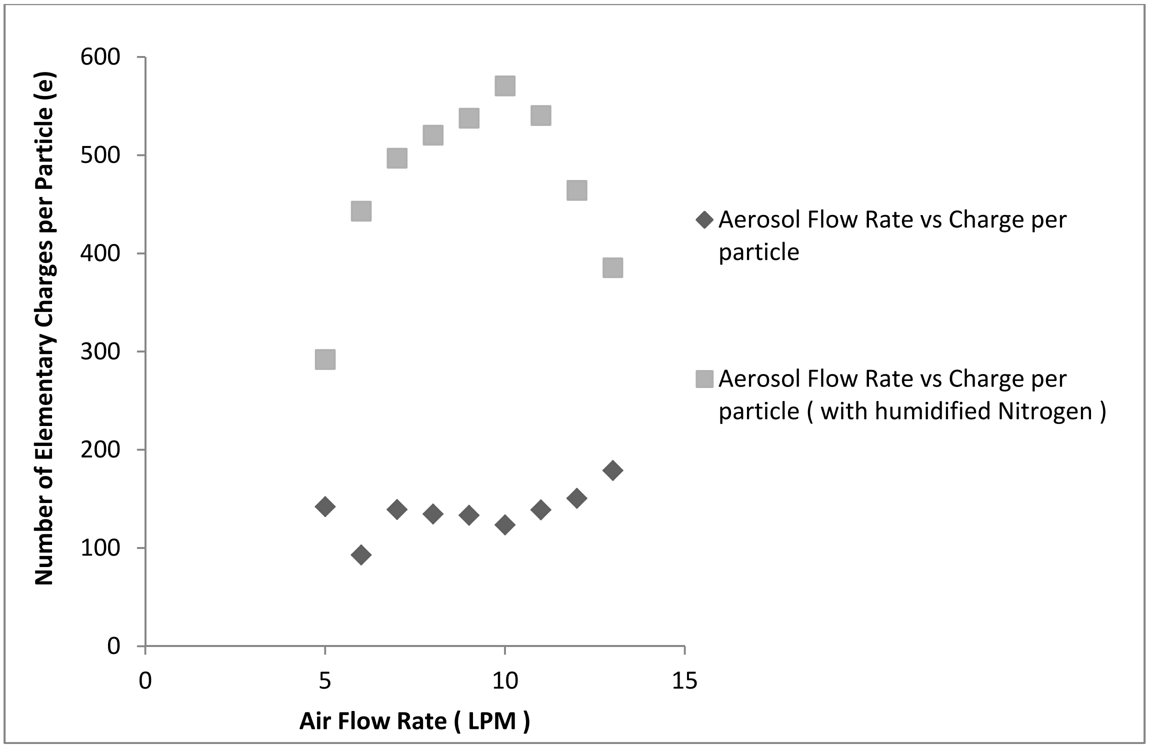


Figure 5.1 – Comparison of charge per particle of coal dust in normal atmosphere and presence of humidified nitrogen.

The results show that in both cases of normal atmospheric condition and presence of humidified nitrogen gas, the coal dust has a significant amount of charge on them. In normal atmospheric condition; the charge per particle is nearly constant with an average of 140 e with a slight increase at flow rates higher than 10 LPM. In presence of humidified nitrogen gas; it varies from 291.94 e to 570.56 e, with maxima of 570.56 e occurring at 10 LPM. The second case shows a higher amount of charge due to the presence of water vapor in the gas streamed. These results show that at a constant motor speed, the air flow does not have a considerable effect on the charge per particle because under normal atmospheric condition it stays almost constant.

The second series of tests were performed at 3 different air flow rates of 2, 4 and 6 liters/min and varying the motor speed at 20%, 40%, 60% and 80% of the maximum speed in the same experimental system as shown in Figure 3.1. The figure 5.2 demonstrates the results of that test.

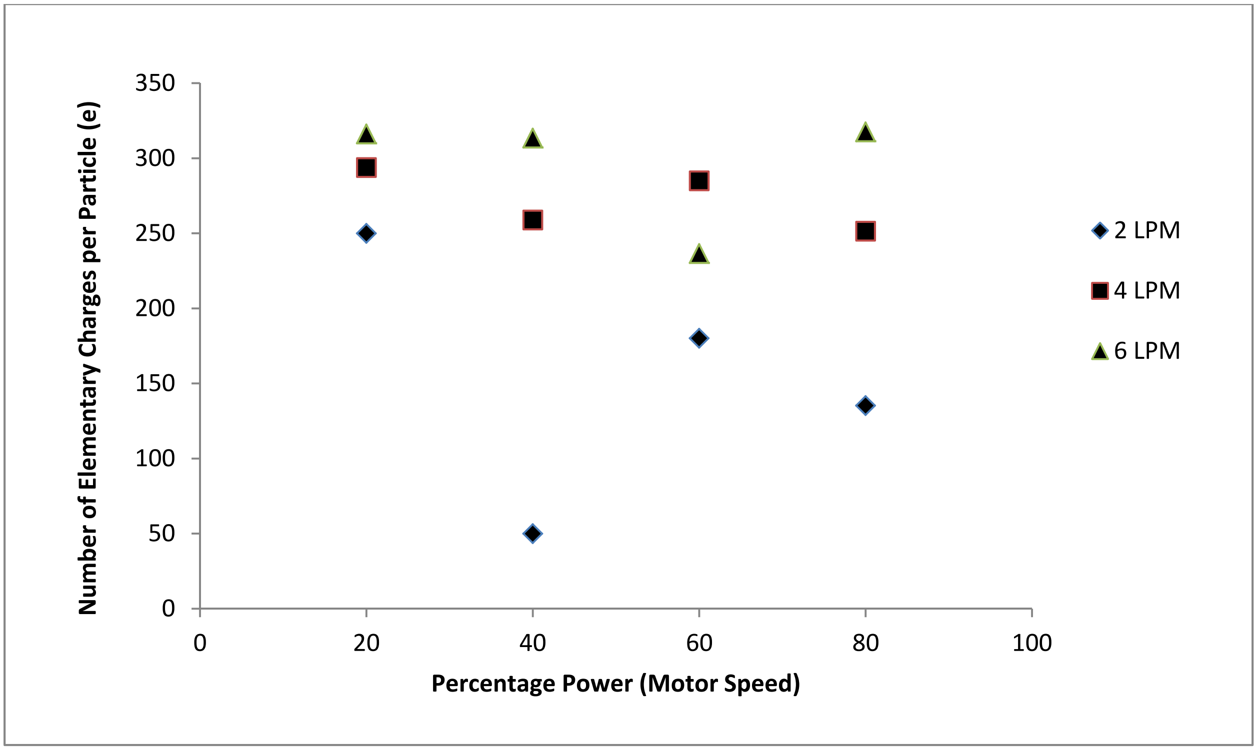


Figure 5.2 Number of Elementary Charge per particle (e) of coal dust at 2, 4 and 6 LPM and 20%, 40%, 60% and 80% motor speeds.

The results demonstrated in Figure 5.2 show that, the number of elementary charges per particle varies from 135.29 e to 316.17 e, with the exception of 50 e at 2 LPM, 40% motor speed. At higher flow rates of 4 and 6 LPM, the charge per particle stays fairly constant between 251.5 e and 317.5 e without showing any dependence on the motor speed. However, it can be observed that in each case of motor speed, the charge per particle consistently increases with the air flow rate. Based on the principle of fluidization of the coal particles in the FBAG, the mass concentration of the coal particles present in the air stream increases with the motor speed as well as the air flow rate. A variation of the motor speed from 20% to 80% has very little change in the charge per particle compared to the change in the charge per particle caused by the increased air flow rate from 2 to 6 LPM. Hence, the results of this study show that the increased air flow rate has a stronger effect than the increased motor speed on the charge per particle of the dispersed coal particles. At the same time, these results also indicate the limitations in the experimental system and measurement techniques. An abrupt increase and decrease in the value of the charge per particle can be caused due to entry of improperly dispersed coal particles into the APS and Aerosol electrometer in amounts more than the usual value at that motor speed and air flow rate. At the same time, the limitations of internal measurement system of both the APS and Aerosol electrometer are also a major factor in this study. There were certain limitations of the experimental system as well. A more leak proof experimental system was required which would prevent the interference of external factors such as unnecessary foreign dust or water vapor inside the chamber and lead to more accurate measurement of the samples of coal particles. In spite of the limitations, the experiments performed and results determined show that coal particles dispersed by the FBAG have an appreciable amount of charge. The charge per particle is dependent on the FBAG operating conditions of motor speed and air flow rate. The size distribution of the coal particles varied from 0.7 to 1.3 μm with an average of 0.9 μm. Hence it is justified to use the particle diameter as 0.9 μm for all calculations of capture efficiency.

Experiments were carried out to calibrate the mass concentration of the coal particles dispersed by the FBAG as a function of the motor speed. For this purpose, the air stream containing coal particles was flowed through a seal chamber where the coal particles were deposited in filter papers. The filter papers were weighed before and after the experiment and the mass concentration of the coal particles in the air stream was calculated using equation (4.2). The experiments were carried out at two flow rates of 12 liters/min and 20 liters/min for 30 minutes. Figure 5.3 shows the variation of the mass concentration of the coal particles with the motor speed.

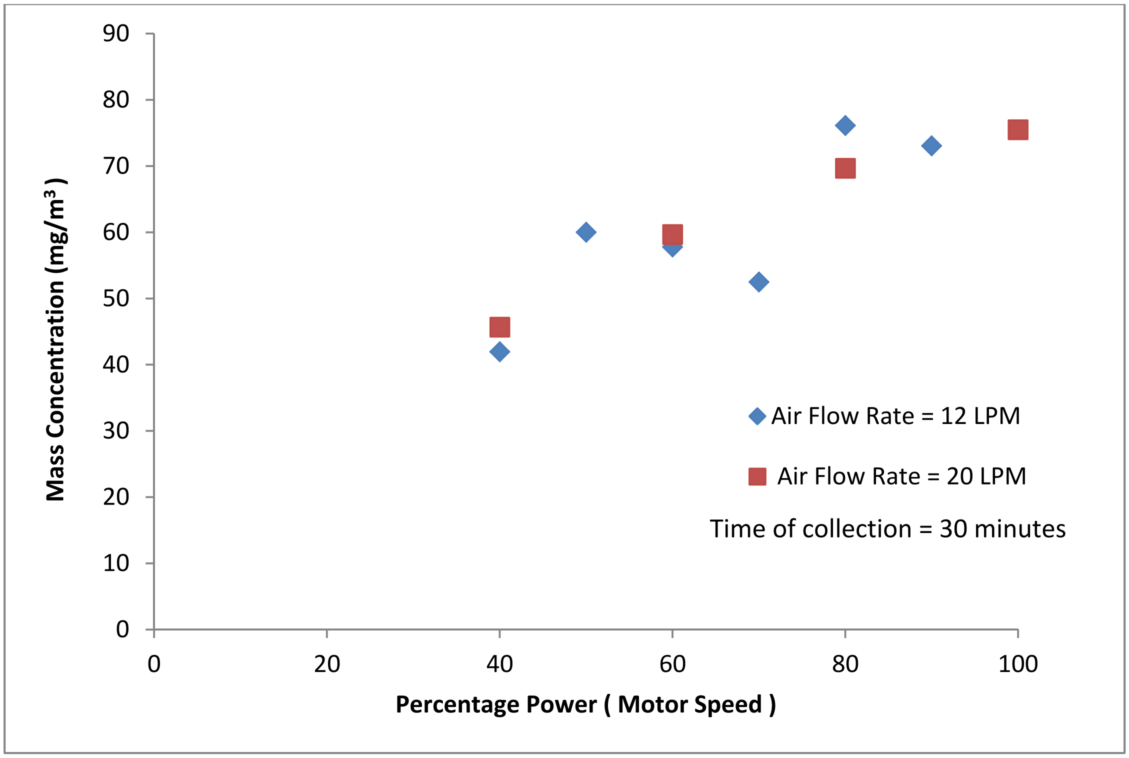


Figure 5.3 – Variation of Mass concentration of coal particles (mg/ m^3) with the motor speed.

5.2 Water Droplet Distribution

It was necessary to determine an accurate size distribution of water drops generated by the ultrasonic atomizer in the presence of counter current air flow in the scrubbing column in order to calculate the capture efficiencies of the drops. Two methods were used for this purpose. In the first method, a series of experiments were performed where water was collected at the bottom of the scrubbing column in the presence of counter current air flow. As explained in Chapter 4, the loss of water caused due to smaller drops being carried away by the air and the drops hitting the column wall was quantified using the experimental results of Table 4.2. The experimental results of Table 4.2 were used to determine the volume percentage lost for the experimental air flow rates used for the scrubbing experiments as shown in Table 4.3. It was assumed that drops of size smaller with terminal velocities lower than the upward velocity of the air flowing through the column were carried away by the upward air flow with higher velocity. On the basis of this assumption, the manufacturer supplied specification data sheet (Figure 4.1) was modified to Figure 4.2 which shows the cumulative volume percentage as a function of the drop diameter. Combining the interpolation results of percentage volume collected for every air flow rate (Table 4.2) and the cumulative volume percentage for the corresponding drop diameter (Figure 4.3), Table 4.3 was generated. Table 4.3 presents final results of this experimental drop diameter distribution study where the air flow rate with the corresponding minimum drop diameter is shown.

The second method for calculation of the minimum drop diameter was comparing the upward air velocity with the terminal velocity of water drops and using the criteria of $V_g < V_i$ (where V_g is the upward air velocity and V_i is the terminal velocity of water drop) to determine the minimum drop diameter (D_i). Similar to the first method, the minimum drop diameter thus determined would be the smallest drop having a terminal velocity greater than the upward air velocity. The results of this study have been presented in Table 4.4. A comparison between the minimum diameters obtained by the two methods is presented in Table 5.1.

Table 5.1

Comparison between the minimum drop diameters determined for the corresponding air flow rate by the two methods

Air Flow Rate Q_g (Liter/min)		Minimum Diameter (μm) determined from water collection experiment (Method 1)		Minimum Diameter (μm) determined using $V_g < V_i$ criteria (Method 2)
4		15		25
5		15		25
7		20		30
8		20		40
9		25		40
10		25		40

From Table 5.1, that can be seen that for a particular air flow rate, the experimentally determined minimum diameter from the first method is lower than that determined from the second method. This is contradictory since both the methods should give the same minimum drop diameter and the corresponding drop size distribution. For instance, at 4 liters/min air flow, the upward air velocity is 0.0146 m/s. Hence the minimum terminal velocity of a water drop to be present in the particle capture process should be greater than 0.0146 m/s. Hence the second method which uses the criteria of $V_g < V_i$, gives the minimum drop diameter as 25 µm which has a terminal velocity of 0.0189 m/s. However the first method gives the minimum drop diameter as 15 µm having a terminal velocity of 0.00685 m/s which is less than 0.0146 m/s. The possible reason is that the actual upward air velocity is much lower than the calculated velocity for a given air flow rate. For example, since the water collection experiment determines that a drop of terminal velocity 0.00685 m/s exists in the column and it is not carried by the air, the upward velocity is lower than 0.00685 m/s instead of being 0.0146 m/s (the calculated upward velocity for a 4 LPM air flow). This happens due to leaks in the experimental system which leads to loss of air such that actual air flow rate is lower than flow rate shown by the rotameter on the FBAG. In an ideal scenario, where the experimental system would be 100% leak proof without any loss of air, the minimum diameter determined by the water collection experiment would be either equal to or greater than the one determined by the criteria of $V_g < V_i$. There is a possibility of the minimum diameter determined by the water collection being greater because of the loss of water drops occurring by the ones hitting the column walls which has been ignored while calculating the minimum drop diameter using the second method. Another limitation of both of the methods of minimum drop diameter determination is that the loss of water occurring due to a certain percentage of larger drops hitting the column walls is ignored in this study. There are drops generated by the ultrasonic atomizer hitting the column in spite of having diameters greater than the minimum diameters determined by the two methods and having terminal velocities higher than the upward air velocity. It was not possible to quantify the size or volume percentage of these drops. Hence the only assumption was that smaller drops having terminal velocities higher than the upward air velocity were carried away and the effect of drops hitting the column wall was ignored. The two drop size distributions determined by two methods were used to calculate two separate capture efficiencies (η_1& η_2) and both the results have been compared with the theoretically predicted capture efficiencies by the models given by Slinn (1983) and H.T.Kim (2001).

5.3 Scrubber Efficiency ($\eta_{scrubber}$) and Capture Efficiencies (η_1& η_2)

The scrubber efficiency and the capture efficiency of a single water drop has been calculated using the experimental results where the air flow rate and water flow rate has been varied and the input and output number concentration of the coal particles have been measured using the APS. The scrubber efficiency ($\eta_{scrubber}$) is calculated using equation (4.15). The Figure 5.4 shows the variation of the $\eta_{scrubber}$ with the water flow rate for various air flow rates.

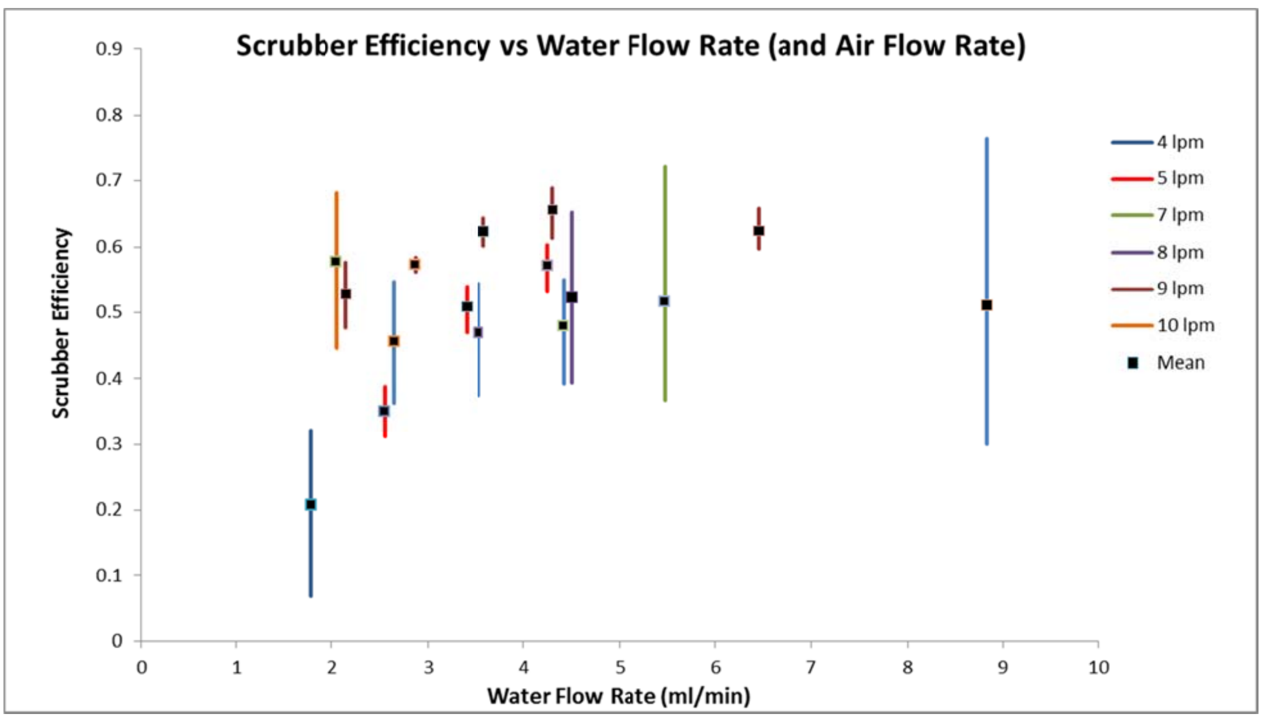


Figure 5.4 – Scrubber Efficiency vs Water Flow Rate in ml/min (and Air Flow Rate in Liters/min)

The water flow rate was varied from 2 to 10 ml/min and the air flow rate was varied from 4 to 10 liters/min. The water flow rate was corrected to the actual value taking into account the loss for every value of air flow rate using the results from Table 4.2. Figure 5.4 shows that for a particular air flow rate, the scrubber efficiency increases with the increase in the water flow rate. For example at an air flow rate of 4 liters/min, the $\eta_{scrubber}$ is 32.07% at a water flow rate of 1.77 ml/min (corrected value of 2 ml/min) and it increases up to 76.47% at 8.83 ml/min (corrected value of 10 ml/min). A similar trend can be observed for an air flow of 5 liters/min and 9 liters/min. In case of 5 liters/min the scrubber efficiency increases from 38.79% at 2.55 ml/min (corrected value of 3 ml/min) to 60.3% at 4.25 ml/min (corrected value of 5 ml/min). In case of 9 liters/min the scrubber efficiency shows a maximum of 68.86% at 4.3 ml/min (corrected value of 6 ml/min). Increase in air flow rate indicates an increase in mass concentration of the coal particles. This shows that the effectiveness of the scrubber increases with the increase in the mass concentration of the coal particles. The scrubber efficiency overall varies from 35% to 70% (excepting the values below 30% at 4 liters/min and 1.77 ml) with average of 53.5%. These results prove that the design of the scrubbing column was quite effective in capturing the coal particles dispersed by FBAG using the ultrasonic atomizer.

The figures 5.5 and 5.6 show the variations of the capture efficiencies ($\eta_1 \& \eta_2$) of a single drop with the water flow rate for various air flow rates. As explained in Chapter 4, there were two methods of calculating the single drop capture efficiency. The first method used the drop size distribution determined from the water collection experiment and the results from Tables 4.3. The capture efficiency calculated thus was denoted as η_1. The second method used the drop size distribution determined using the criteria of terminal velocity of the smallest drop (V_i) > upward air velocity (V_g) and the results from Table 4.4. The capture efficiency calculated thus was denoted as η_2.

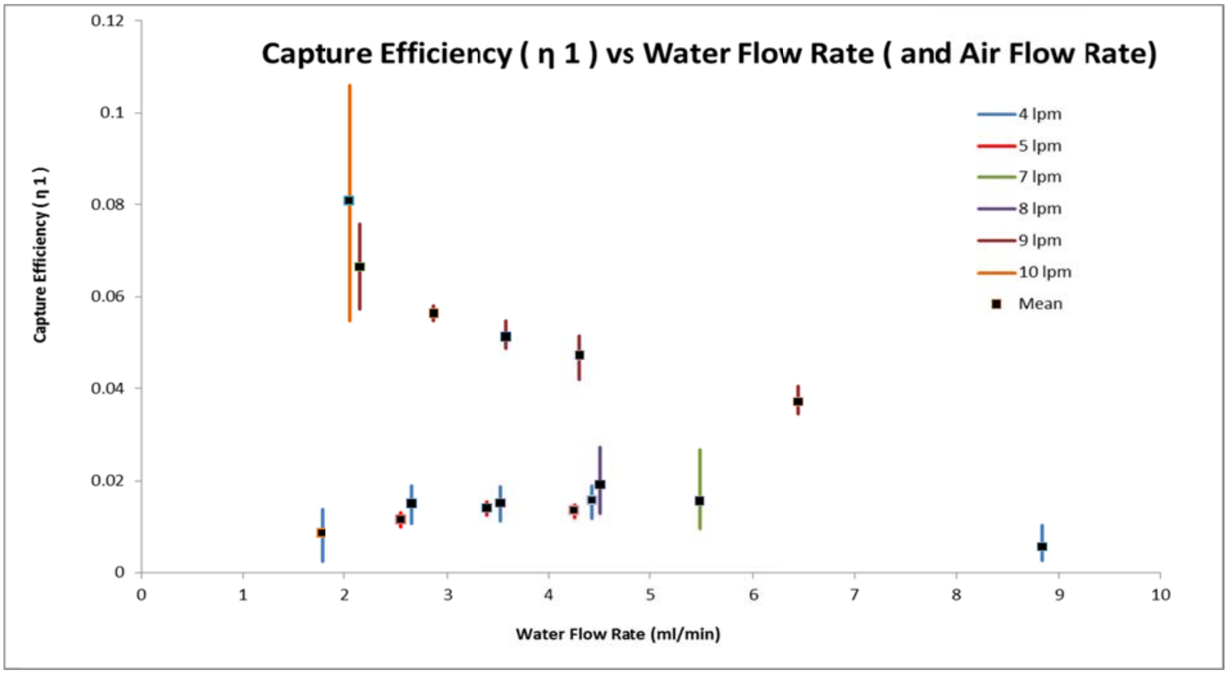


Figure 5.5 Capture Efficiency (η_1) variation Water Flow Rate in ml/min (and Air Flow Rate in Liters/min)

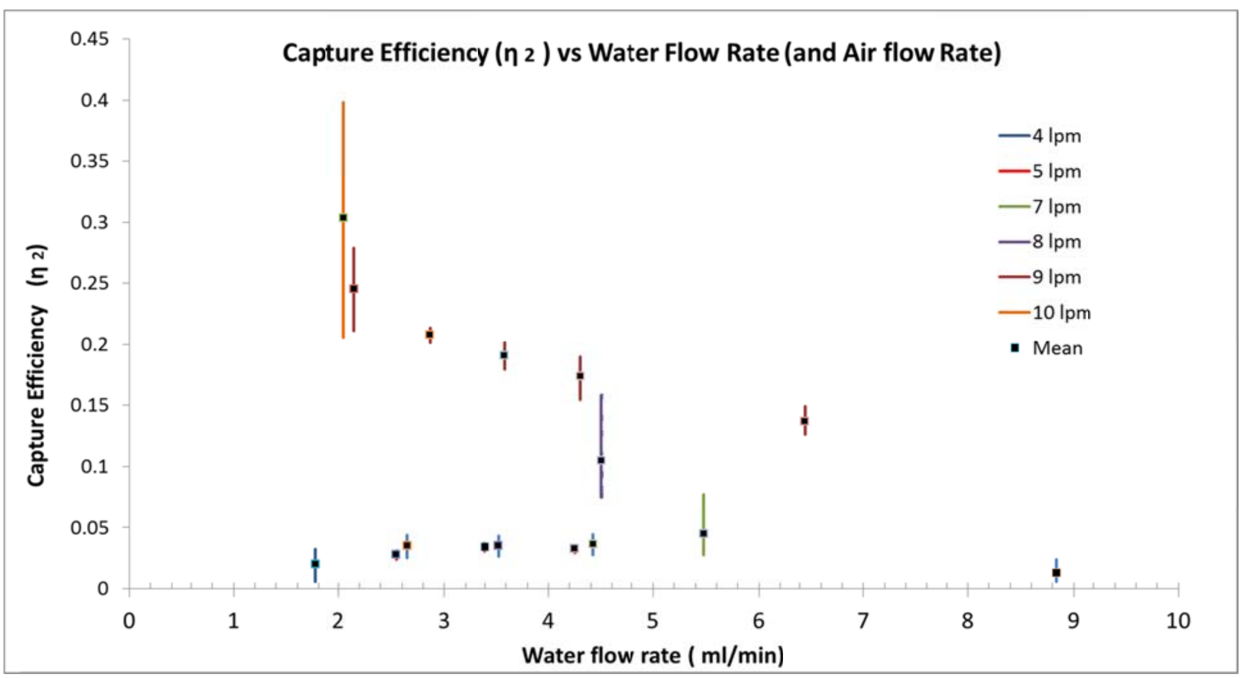


Figure 5.6 Capture Efficiency (η_2) variation with Water Flow Rate in ml/min (and Air Flow Rate in Liters/min)

Figures 5.5 and 5.6 show that the capture efficiencies (η_1& η_2) do not vary to a large extent when the air flow rate is between 4 and 7 liters/min. There is an increase in capture efficiency of both η_1 and η_2 when the air flow rate is 8, 9 and 10 liters/min. Both the capture efficiencies (η_1& η_2) show the same variation with the change in water and air flow rate. However the capture efficiency (η_1) has an overall lower value for every case of water and air flow rate on comparison with the capture efficiency (η_2). For example at an air flow rate of 9 liters/min the capture efficiency decreases with the increase in the water flow rate from 2.15 to 6.48 ml/min in both the cases of η_1& η_2. The value of η_1 however decreases from 7.58% (at 2.15 ml/min) to 3.64% (at 6.48 ml/min), where the value of η_2 decreases from 26.37% (at 2.15 ml/min) to 12.75% (at 6.48 ml/min). The reason behind this increase in capture efficiency can be explained by basis of its calculation using equations (4.13) and (4.14). The numerical term; $Y = \sum\left(\frac{V_{t_i} W_i}{D_i V_i}\right)$ depends upon the drop size distribution chosen which it turn depends upon the method used for determination of minimum drop diameter. Table 5.1 shows that, for an air flow rate of 9 liter/min, the minimum diameter given by the first method is 25 µm and that by the second method is 40 µm. When 25 µm is used as the smallest drop diameter, the drop size distribution would give a greater value of Y as compared to the value of Y generated when 40 µm is used as the smallest diameter for determining the drop size distribution. This happens because in case of the former, there is a larger drop distribution including drops of diameter 25 and 30 µm and more number of terms in the summation of Y. As a result, when the first method of drop size distribution is chosen, a higher value of Y generates a lower value of capture efficiency (η_1). Whereas, the second method gives a drop size distribution containing lesser number of summation terms for Y and results in a lower value of Y and a higher value of capture efficiency (η_2). The same explanation can be given for the other cases of air flow rates of 4, 7, 8 and 10 liters/min where the value of η_1 is lower than that of η_2 because of the method of drop size distribution selection for capture efficiency calculation.

In comparison with figures 5.5 and 5.6, it can be observed that the $\eta_{scrubber}$ varied much less with the change in water flow rate as shown in Figure 5.4. The common observation from Figures 5.5 and 5.6 is that the values of both η_1 and η_2 increases with the increase in air flow rate. Also, the values of η_1 and η_2 increases for a particular air flow rate when the water flow rate decreases. A possible explanation of this trend is the lack of variation of the scrubber efficiency ($\eta_{scrubber}$) along with the change of air flow rate at a constant water flow rate or vice versa. For example at a water flow rate of 2.55 ml/min, $\eta_{scrubber}$ is 31.25% (at an air flow of 5 liters/min) and it increases up to 68.12% at a water flow rate of 2.05 ml/min and air flow rate of 10 liters/min. Comparing this situation with the same in figures 5.5 and 5.6, a similar trend can be observed with η_1& η_2 increasing from 1.17% and 2.43% (at an air flow rate of 5 liters/min and water flow rate of 2.55 ml/min) respectively to 10.59% and 39.81% (at an air flow rate of 10 liters/min and water flow rate of 2.05 ml/min) respectively. This trend of the scrubber is quite contradictory to the prediction that the scrubber efficiency would decrease with the increase in air flow rate leading to the increase in the mass concentration of the coal particles. A possible reason behind this could be that at a higher air flow rate the coal particles are more uniformly dispersed compared to the dispersion at lower air flow rates. Due to better dispersion, the capture of coal particle is easier by the water drops leading to higher capture efficiency and scrubber efficiency. Overall this study shows the single drop capture efficiency to be as high as 10.6% for η_1 and 39.81% for η_2.

5.4 Comparison between Experimental Capture Efficiencies (η_1& η_2) and Theoretical Average Efficiencies (η_{avg})

The experimental capture efficiencies (η_1& η_2) have been compared with the theoretical average efficiencies (η_{avg}) using equation (4.20).

$$\eta_{avg} = \frac{\sum \frac{\eta_i V_{t_i} W_i}{V_i D_i}}{\sum \frac{V_{t_i} W_i}{V_i D_i}} \qquad (4.20)$$

According to the theoretical models of Slinn (1983) and H. T. Kim (2001), the capture efficiency is a function of the drop diameter (D_i) and the particle diameter (d_p). In this study for the purpose of theoretically determining the capture efficiencies by the equation (4.20), the particle diameter has been assumed to have a constant value of 0.9 µm. The drop diameter (D_i) has been determined on the basis of the drop size distribution method used for capture efficiency calculation. The theoretical models of Slinn (1983) and H. T. Kim (2001) have been used to calculate the capture efficiencies (η_i) separately for the drop distribution corresponding to the experimental capture efficiency (η_1& η_2). The results have been represented graphically in the following four figures:

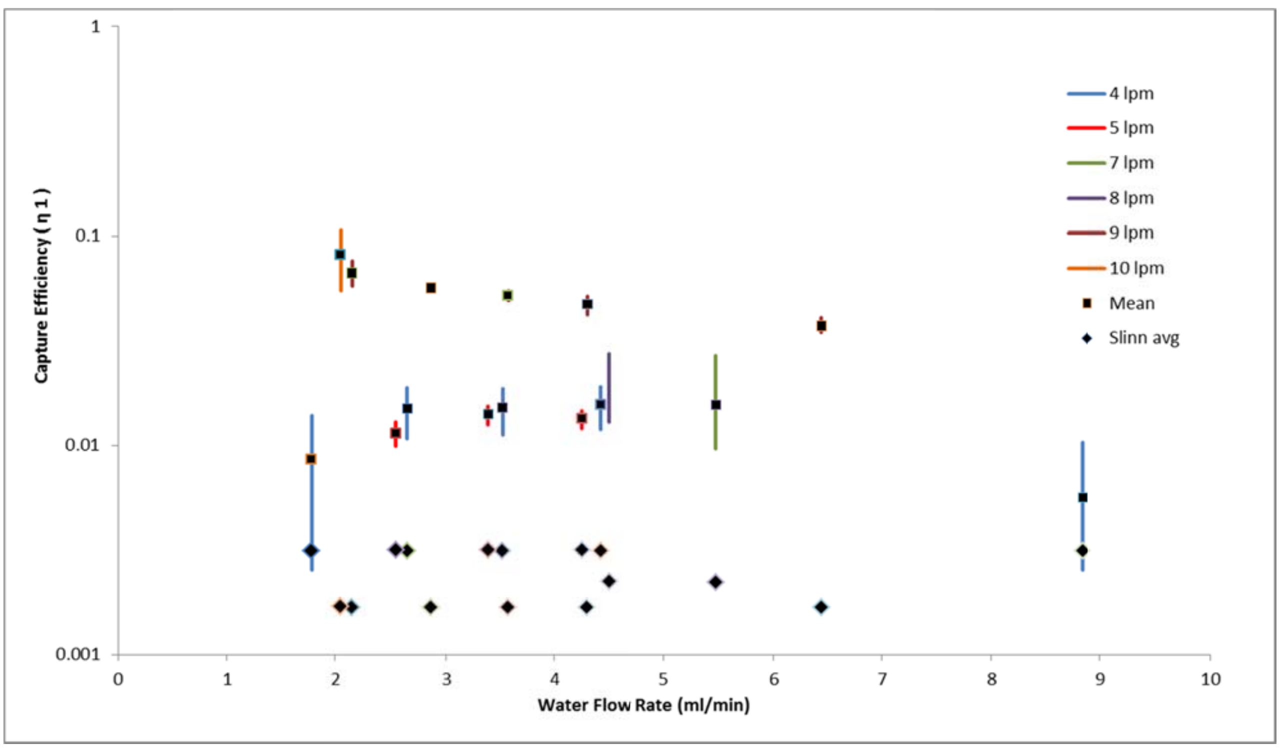


Figure 5.7 –Comparison of capture efficiency (η_1) and η_{avg} (Slinn 1983)

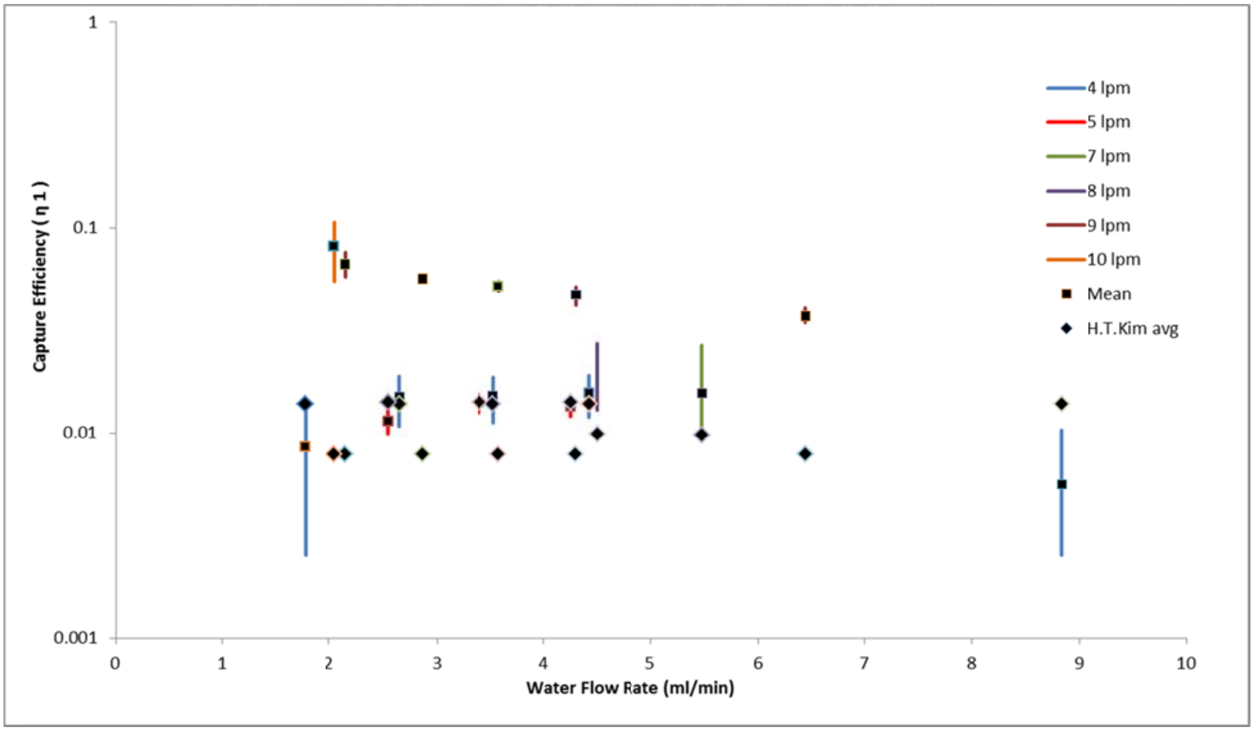


Figure 5.8 - Comparison of capture efficiency (η_1) and η_{avg} (H. T. Kim 2001)

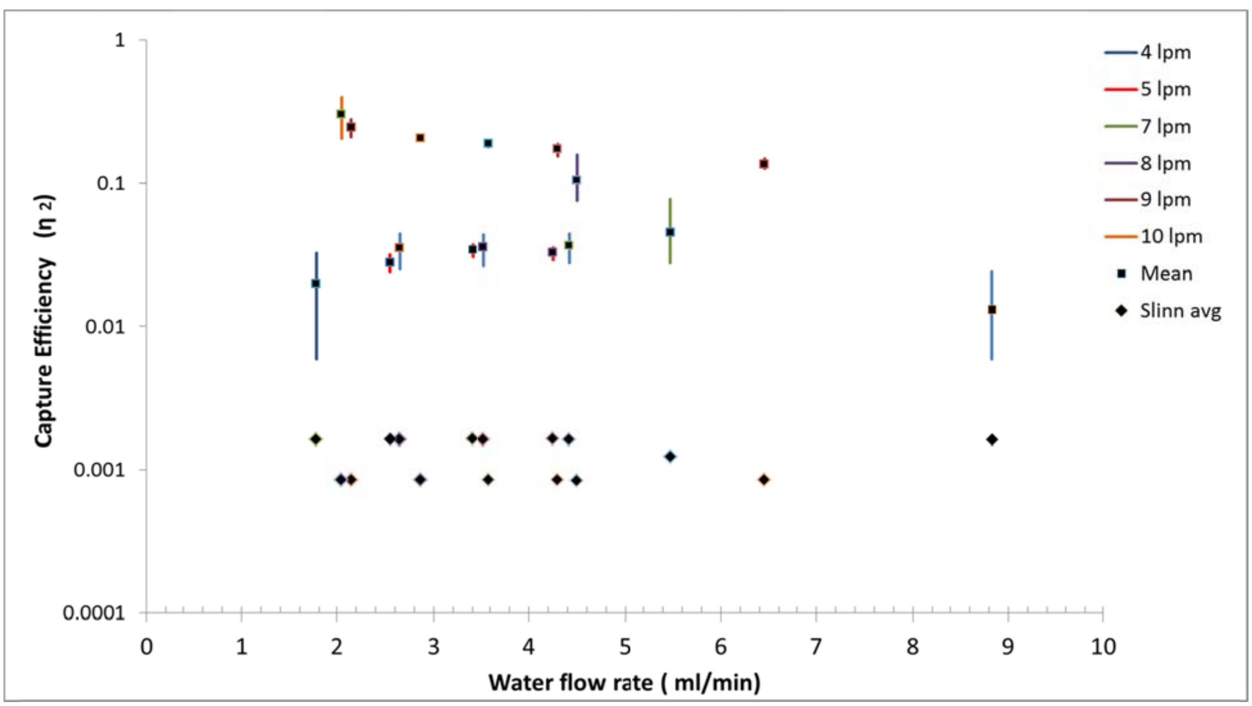


Figure 5.9 - Comparison of capture efficiency (η_2) and η_{avg} (Slinn 1983)

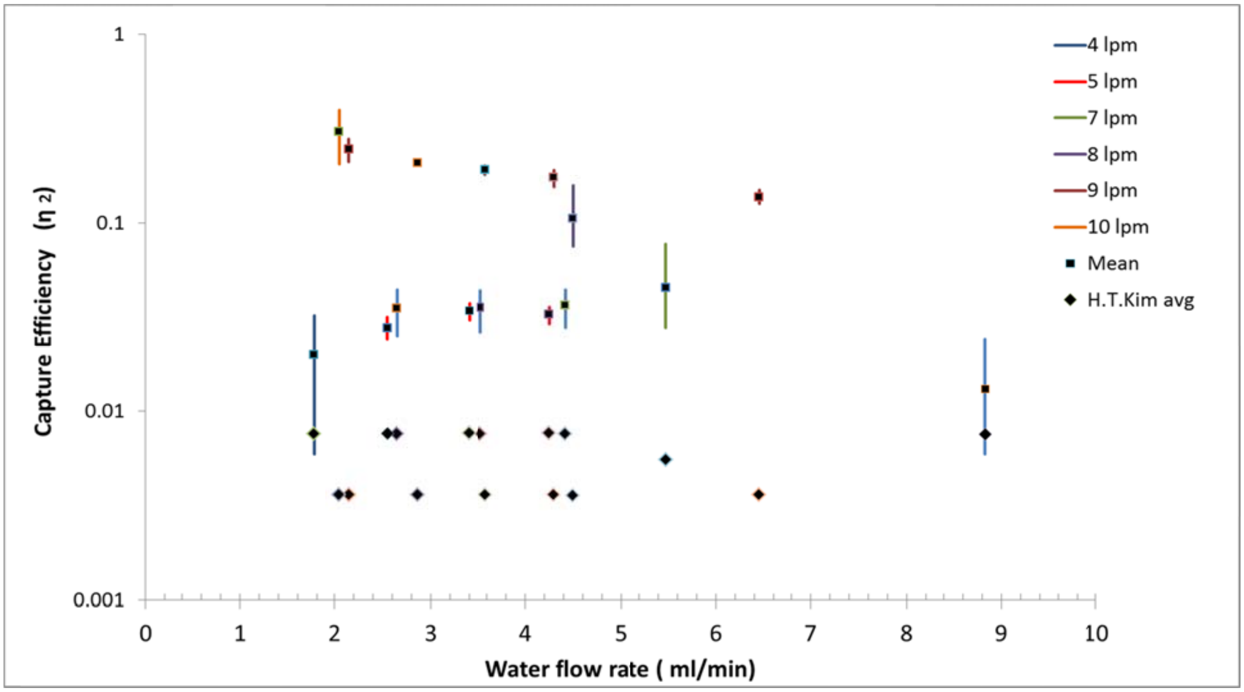


Figure 5.10 - Comparison of capture efficiency (η_2) and η_{avg} (H. T. Kim 2001)

Figures 5.7 and 5.8 show the comparison of the experimental capture efficiency (η_1) with the capture efficiencies predicted by the two models; Slinn (1983) and H. T. Kim (2001) respectively. Figures 5.9 and 5.10 show the comparison of the experimental capture efficiency (η_2) with the capture efficiencies predicted by the two models; Slinn (1983) and (H. T. Kim 2001) respectively. Figures 5.7 and 5.8 show that the average capture efficiencies ($\eta_{avg}s$) based on H. T. Kim (2001) are much closer to the experimentally determined values of η_1 as compared to the $\eta_{avg}s$ calculated based on Slinn (1983). It can be seen that the $\eta_{avg}s$ calculated from the H. T. Kim (2001) based model fall within the range of the experimentally determined capture efficiencies (η_1) with certain exceptions, whereas the $\eta_{avg}s$ calculated from the Slinn (1983) model are outside the range of the values of the capture efficiencies (η_1). This occurs because the model given by Slinn (1983) takes into account only the effect of Brownian diffusion for particle capture by the water drops whereas the model given by H. T. Kim (2001) accounts for all the three effects of Brownian diffusion, interception and impaction. Although impaction and interception may not have a major role in particle capture since the particles are less than 1.3 µm, but the effect of these factor cannot be completely ignored. The validity of the more improved model given by H. T. Kim (2001) compared to Slinn (1983) has been proved by this study. Observation of Figures 5.9 and 5.10 reveals a similar conclusion. The experimentally determined capture efficiencies (η_2) are of a much higher magnitude overall than those determined by the first method (η_1). The comparison of the theoretically determined average efficiencies ($\eta_{avg}s$) with $\eta_2 s$ from Figures 5.9 and 5.10 show that for both the cases of Slinn (1983) and H. T. Kim (2001), the $\eta_{avg}s$ are outside the range of the experimental efficiencies. In case of H. T. Kim (2001), the $\eta_{avg}s$ differ from the $\eta_2 s$ by an order of 10, whereas for the case of Slinn (1983) the difference is of the order of 10^2. The difference is greater between $\eta_{avg}s$ and $\eta_2 s$ for the model given by Slinn (1983) as compared to that given by H. T. Kim (2001), which once again proves that the H. T. Kim (2001) model is more accurate in predicting the single water drop capture efficiency. The large order of difference between the theoretical and experimental values for the case of η_2 as compared to the experimental values of η_1, proves the better accuracy of the method of determination of capture efficiency by the 1st method. This result proves that the method of minimum drop diameter determination using the experiment of water collection in presence of counter current air flow is more accurate for estimating the drop size distribution compared that theoretical method of minimum drop diameter determination using the criteria of smallest drop having a terminal velocity higher than the upward air velocity.

Figures 5.11 and 5.12 compare the scrubber efficiencies with the theoretical averages calculated using both the models of Slinn (1983) and H. T. Kim (2001) respectively. It can be seen that the theoretical averages of H. T. Kim (2001) show better agreement with the scrubber efficiencies than the theoretical averages of Slinn (1983). These show that the prediction given by H. T. Kim (2001) is more accurate than that by Slinn (1983).

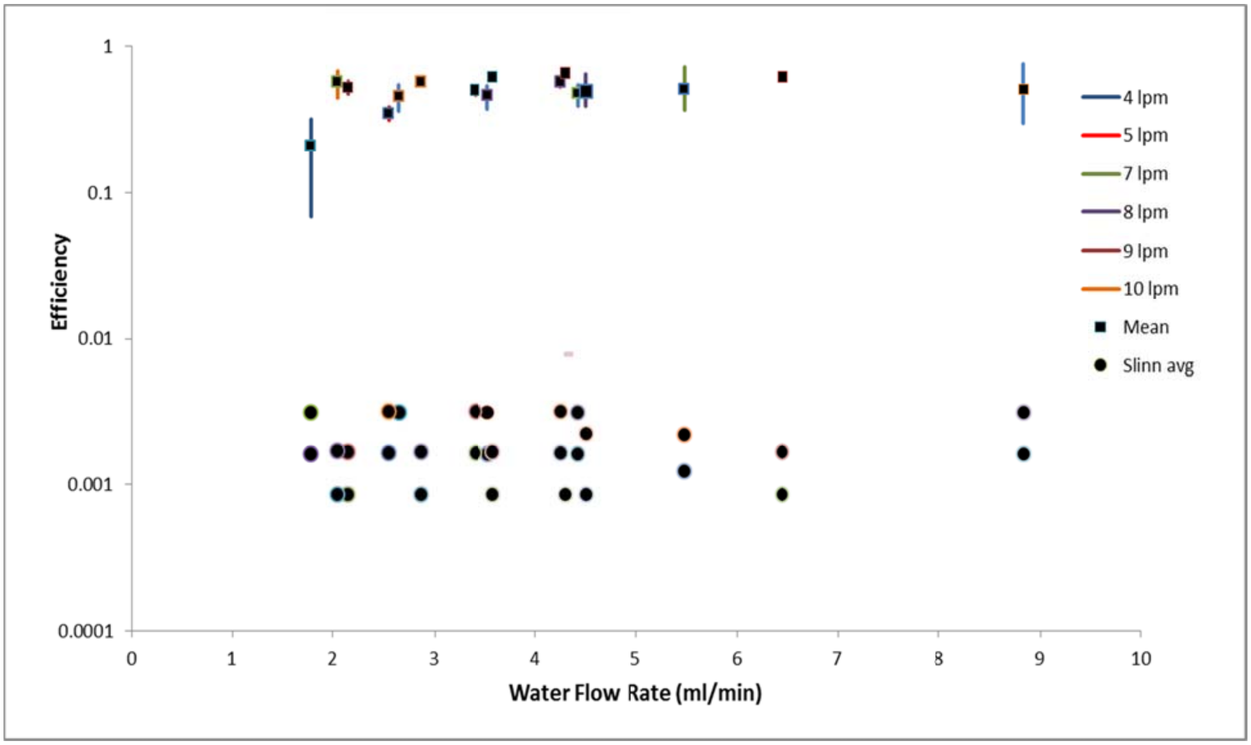


Figure 5.11 – Comparison of scrubber efficiency ($\eta_{scrubber}$) and η_{avg} (Slinn 1983)

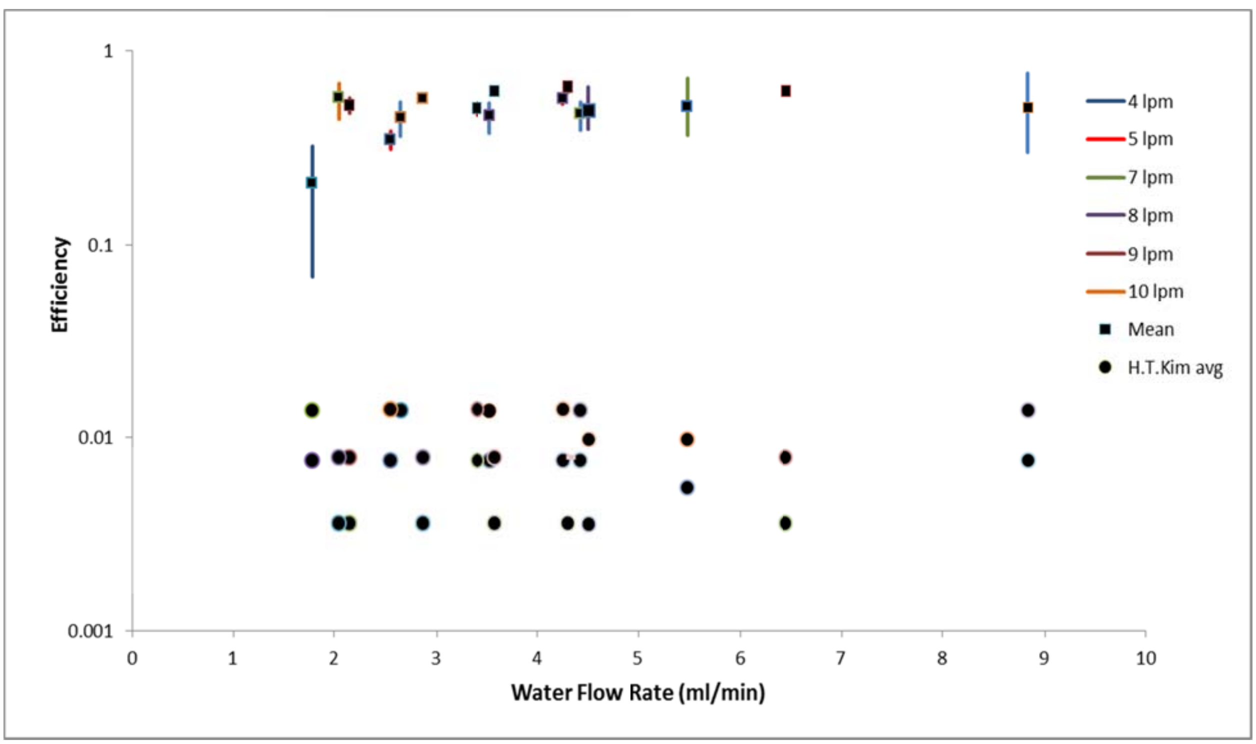


Figure 5.12 – Comparison of scrubber efficiency ($\eta_{scrubber}$) and η_{avg} (H.T.Kim 2001)

The agreement of experimentally determined capture efficiency (η_1), where the drop size distribution has been determined experimentally, with the theoretical predictions of the model given by H. T. Kim (2001), where all the three effects of Brownian diffusion, interception and impaction has been taken into consideration, has been shown by Figure 5.8. These agreements of the experimental and theoretical values strongly support the experiments performed in this research along with the mathematical models used with the stated assumptions.

5.5 Prediction of charge of water drop

The experimentally determined capture efficiencies (η_1) do not however completely match with the theoretical averages of capture efficiencies predicted by H. T. Kim (2001). The $\eta_{avg}s$ predicted by the model of H. T. Kim (2001) are consistently lower than the η_1 values, in spite of the fact that the H. T. Kim (2001) model considers the three effects of Brownian diffusion, interception and impaction for particle capture. The possible reason for this is the presence of Coulombic attraction for particle capture. This study shows the presence of positive electric charge in the coal particles with an average value of 140 elementary units of charge (e). Hence it can be postulated that the water drop carry certain amount of negative charge that is responsible for the enhanced capture efficiencies. In order to predict the amount of negative charge present in the water drops, the following equations given by Dhariwal, Hall et al. (1993) were used –

$$\eta = -4K_E \tag{5.1}$$

where η is the capture efficiency of the drop and K_E is the Coulombic force given by

$$K_E = \frac{C_c Q_p Q_c}{3\pi^2 D^2 d_p \mu V_g \varepsilon_o} \tag{5.2}$$

where Q_p and Q_c are the particle and drop charges, and ε_0 is the dielectric constant of the surrounding fluid. An average water drop diameter (D) of 55 µm, particle diameter (d_p) of 0.9 µm, average particle charge of 140 e or 2.24 x 10^{-17} C and a dielectric constant of 1.000596 of air were assumed. Figure 5.1 shows the predicted results of the water drop charge with the corresponding experimentally determined capture efficiencies. It can be predicted that for a range of capture efficiency between 0.44% and 39.81%, the water drop would have a charge in the range between - 2 x 10^{-6} C and -2 x 10^{-4} C. The predicted charges are quite high compared to the coal particle charges. The high value of negative charges can give a possible explanation of the enhanced experimental capture efficiencies. It can be predicted that apart from the three effects of Brownian diffusion, interception and impaction, the Coulombic force of attraction was also responsible for the charged coal particle capture by the water drops.

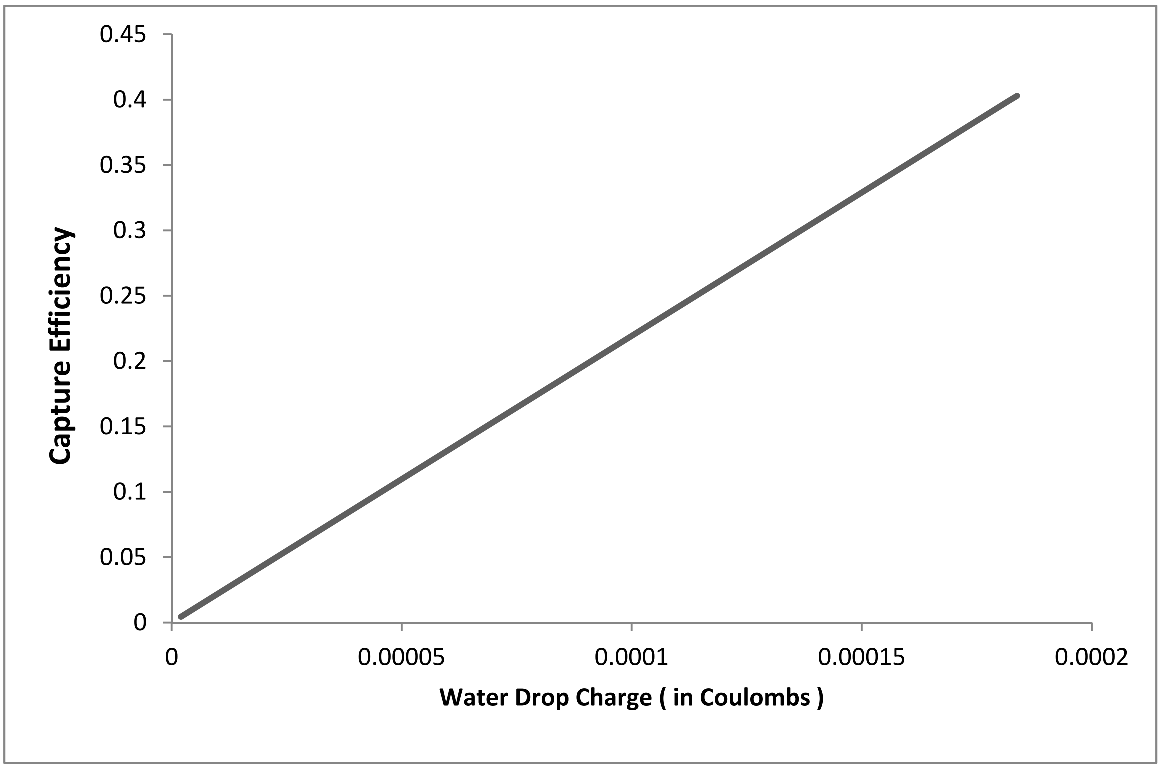


Figure 5.13 – Prediction of water drop charge for the corresponding experimentally determined capture efficiency

Chapter 6

Conclusions

This research explores the possibilities of dust removal of submicron (less than 1 μm) coal particles dispersed in an air stream using water drops of sizes between 0.5 to 90 μm in an experimental scrubbing column. The results of coal particle characterization experiments show that submicron coal particles dispersed in an air stream by the Fluidized Bed Aerosol Generator (FBAG); carry a significant amount of charge varying from 100 to 350 elementary units of charge (e). The charge strongly depends upon the air flow rate and the amount of dispersion. The charge per particle can also be as high as 600 elementary charges in a humidified environment. This study clearly proves the presence of appreciable charge in submicron coal particle which can be used for enhanced dust removal by Coulombic attraction.

The ultrasonic atomizer experiments were carried out to determine the drop size distribution of the vertically falling drops inside the scrubbing column in the presence of counter current air flow. Results showed that within the experimental range of air flow (4 to 10 liters/min); a loss as high as 30% can occur due to drops being carried away by air and wall loss. On the basis of the manufacturer specifications and the assumption that smaller drops are lost due to the above reasons; drops from sizes 25 to 90 μm have taken part in the scrubbing process

The study of the single drop capture efficiency as well as the scrubber efficiency was performed using experimental results of the scrubbing process and implementation of appropriate mathematical models. The scrubber efficiency steadily increases with the increase in water and decrease air flow rate reaching a maximum of 76.47% at 4 liters/min (air flow rate) and 8.83 ml/min (water flow rate) and with an average of approximately 55%. Presence of more water drops and low mass concentration of coal particles at a high water flow rate and low air flow rate is the reason for this. A high steady value of scrubber efficiency indicates enhanced dust removal and justifies the basis of the scrubber column design as well as modeling techniques used for measurement.

Experimental results of single drop capture efficiency show that at higher air flow rates of 10 liters/min, the capture efficiency is as high as 39.81%. When the air flow rate is between 4 to 8 Liters/min; the capture efficiency is evaluated to be less than 10%. The capture efficiency calculation strongly depended on the water drop size distribution. The two methods were used for the determination of drop size distribution. The first method involved collection of water sprayed by the atomizer at the bottom of the scrubbing column in presence of upward air flow. The second method was a theoretical method where the criteria of smallest drop diameter having a terminal velocity higher than the upward air velocity was used. The experimental capture efficiencies ($\eta_1 \& \eta_2$) were compared with theoretically determined average capture efficiencies (η_{avg}) based on two separate models given by Slinn (1983) and H. T. Kim (2001). The comparison results show that the experimentally determined efficiency (η_1) is in agreement with the theoretical averages of the model given by H. T. Kim (2001). This agreement proves that the model given by H. T. Kim (2001) is more accurate than the one given by Slinn (1983) because the former considers the combined effect of Brownian diffusion, interception and impaction for particle capture unlike the model by Slinn (1983) which is only based on Brownian diffusion. The agreement also shows that the first method of capture efficiency calculation where the water drop size distribution was determined experimentally, was more accurate than the second method used; where the theoretical criteria of terminal velocity of the smallest drop being higher than the upward air velocity was used.

The results of the charge distribution of the coal particles and the capture efficiencies evaluated were used to predict the amount of opposite charge present in the water drops. Since the experimental capture efficiencies were higher than that predicted by the theoretical models, a possible explanation of the enhanced capture efficiencies was the effect of Coulombic attraction between the charged coal particles and oppositely charged water drops. It was predicted that the water drop would have a charge in the range between - 2 x 10^{-6} C and -2 x 10^{-4} C. This validates the postulate that apart from the three effects of Brownian diffusion, interception and impaction, the effect of Coulombic attraction between the positively charged coal particles and negatively charged water drops was responsible for the enhanced capture efficiencies determined experimentally.

The results of this research can be used for industrial applications of dust suppression especially in areas containing submicron dust having the threat of Coal Worker's Pneumoconiosis (CWP). Since it has been proved that submicron coal particles contain significant amount of charge and these can be captured using water drops generated by a water sprayer, a further improved sprayer system that can generate negatively charged drops would definitely improve the capture efficiency of the single drop as well as the scrubber. The results obtained in this study can be used for further research for development of a charge based water sprayer system for better dust removal and reduction of CWP.

Nomenclature

E_o Overall collection efficiency of the scrubber

e Elementary unit of charge = 1.602×10^{-19} C

q Charge per particle expressed as number of elementary units of charge

N_p Number concentration of particles

Q_g Gas flow rate

I Current reading of Aerosol electrometer

C_m Mass concentration of coal particles in the air stream

M Mass of coal particles collected in the filter papers

t Time of collection of coal particles in the filter papers

D Water drop diameter

V Terminal velocity of water drop of diameter, D

Re Reynolds number

Pe Peclet number

C_c Cunningham correction factor

D_i Water drop diameter of i^{th} segment of drop distribution

V_i Terminal velocity of water drop diameter D_i

ρ Density of air

μ Viscosity of air

ρ_d Density of water drop

C_D Drag Coefficient

W_i Water flow rate of drop diameter D_i

η Capture efficiency of single water drop

L Length of scrubber column

V_t Relative velocity of water drops

V_{ti} Relative velocity of water drops of diameter D_i

V_g Upward air velocity

A_c Area of cross-section of the scrubber column

d_p Diameter of coal particle

Sc Schmidt number

λ Mean Free Path

k_b Boltzmann constant

η_{diff} Capture efficiency due to Brownian diffusion

α Volume fraction of drop

σ Viscosity ratio of water to air

D_{diff} Coefficient of mass diffusion

η_{imp} Capture efficiency due to impaction

Stk Stokes number

V_{si} Settling velocity of coal particles

η_{avg} Average capture efficiency evaluated from theoretical models

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