Design Optimization and Experimental Study of a Wet Laminar Electrostatic Precipitator for Enhancing Collection Efficiency of Aerosols

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the Russ College of Engineering and Technology of Ohio University

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This thesis titled
Design Optimization and Experimental Study of a Wet Laminar Electrostatic Precipitator for Enhancing Collection Efficiency of Aerosols

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Power plants operating on coal emit pollutants containing particulates that form hazardous gases. Particulates are a combination of liquid and solid droplets in gas. Particulates are of serious concern to the environment and human beings, as they cause various health problems. Due to these hazards and associated federal regulations, industries have been compelled to develop techniques to capture particulates. A most common approach is an “Electrostatic Precipitator” (ESP). The basic operation of an ESP involves charging of the particulates and collection via electrostatic attraction. The Ohio Coal Research Center at Ohio University has developed a laboratory-scale prototype, Wet Laminar ESP, to enhance collection efficiency of fine particulates, specifically sulfuric acid droplets, due to coals with high sulfur content found around Ohio. This study presents strategies to characterize and optimize the collection efficiency of the wet laminar ESP by evaluating various operating parameters. Characterization of flow is performed by gas velocity measurements with both a pitot tube and velocity transducer. Entrance length is calculated and visualized using smoke streak lines recorded with a video camera. Different particle charging mechanisms are analyzed. Voltage-Current (V-I) characterization using various electrodes was performed to identify optimal values. To match conditions of flue gas emitted from power plants, a solution concentration of
sulfuric acid in water was computed for aerosol generation. While substantial progress has been made in identifying optimal operating parameters, two remaining techniques are detailed for future work. Specifically, an analysis describes the advantages and limitations of different techniques to count and characterize fine aerosols, 2.5μm and smaller. To resolve the limitations of the horizontal LESP, approaches and possible modifications are described, aimed at elevating the chamber gas temperature while minimizing thermal stratification in order to more accurately represent the thermal experience of acid aerosols in a flue gas stack.

Approved: _____________________________________________________________

Carole Ann Womeldorf

Assistant Professor of Mechanical Engineering
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CHAPTER 1: INTRODUCTION

Contamination of air is caused by coal fired power plants and industries which emit various particles including dust, smoke, solid and liquid droplets which are broadly termed as “Particulate matter” (PM). “Particulate matter as a whole can be defined as solid and liquid droplets suspended in gas” (U.S. Environmental Protection Agency). Particles carried by the wind settle everywhere, damaging land by reducing nutrients in soil and water, making it acidic. PM also leads to reduced visibility. Aesthetic appearance is greatly affected because of the continuous deposition of particulates (U.S. Environmental Protection Agency; World Health Organization).

Particulates are classified according to the size, ranging from coarse to fine. Coarse particles are relatively larger, with diameters ranging from 2.5µm – 10µm, designated by US Environment Protection Agency (EPA) as PM_{10}. Fine particles have diameters less than 2.5µm (PM_{2.5}) (U.S. Environmental Protection Agency). Fine particles have a higher probability of entering deep into the lungs and the blood stream thus causing health hazards (World Health Organization). Fine particles are a major concern as they affect public health and welfare. Sources of PM_{2.5} are combustion from various industries, emission of gases like sulfur dioxide by various chemical reactions among others. Exposure to PM_{2.5} can lead to reduced functioning of lungs and increased respiratory problems, leading to diseases such as asthma and bronchitis, which can ultimately cause premature death (U.S. Environmental Protection Agency).
Due to these and many other concerns, the organization which became the Environmental Protection Agency (EPA) drafted the “Clean Air Act” (CAA) in 1963 which established the “National Ambient Air Quality Standards” (NAAQS) to improve the quality of air (U.S. Environmental Protection Agency). With the implementation of standards for PM$_{2.5}$ in 1997 and subsequent revision in 2006, there are restrictions on the industry to adhere to the regulations and work towards implementation (U.S. Environmental Protection Agency ; Robert Esworthy Updated October 6, 2006). EPA designates “non attainment” status to the counties across the country that do not maintain the PM$_{2.5}$ standards. Figure 1.2 shows the counties in Ohio and other Midwest states.
whose pollution level exceeded the desired range for the year 2006 (U.S. Environmental Protection Agency)

Figure 1.2: 2006 PM$_{2.5}$ EPA intended designations

(U.S. Environmental Protection Agency)

http://www.epa.gov/pmdesignations/2006standards/rec/region5.htm#docs

Almost 48% of electrical power is generated by coal burning power plants in the United States (Ackerman, B. A., Hassler, W. T. 1981). This is facilitated by the nation’s rich and cheap coal reserves. These power plants hence form major source of PM$_{2.5}$
(Ackerman, B. A., Hassler, W. T. 1981). Ohio is a state which has large reserve of cheap coal with high sulfur content and boasts of a large number of power plants (Figure 1.3). These power plants make it a major center of air pollution as can be seen from Figure 1.2.

*Figure 1.3: Ohio coal fired power plants*

(Source: Special Report: Ohio River Coal-Fired Power Plants; Monday, December 05, 2005 The Columbus Dispatch).

The health, environmental hazards and federal regulations governed by the EPA compel the industries to maintain the PM standards. Many different types of equipment like cyclone separators, air scrubbers, air stripper and electrostatic precipitators have been
developed to prevent pollutant emission. Electrostatic precipitators (ESP) are widely used, long-lasting, economical, and easy-to-operate devices for the control of particulate matter emission (David J. Bayless et al. 2004, 781). The most common type of ESP as mentioned above incorporates dry collection plates. These dry ESPs have disadvantages like re-entrainment due to rapping (a process whereby the collection membranes are intermittently hammered to dislodge built-up particulate matter), and corrosion (Dr. David J. Bayless, John Caine 2001). But all of the devices have limitations for the smallest particulates PM$_{2.5}$. Innovations have been made to enhance the efficiency of these devices. Instead of dry collection plates, wet ESPs use a repelling plate mechanism to force particulates toward large fiberglass fabric membranes that are covered with a thin layer of flowing water which electrostatically attracts, gathers and flushes away the PM (Dr. David J. Bayless, John Caine 2001). Although infrequently implemented at this time, wet ESPs are less expensive and provide increased collection efficiency over the standard dry ESP. And unlike the dry ESP there is no need for hammering and no resultant re-entrainment. Additionally, some PM may be soluble in water so they can be easily removed by water circulation. An added benefit of wet ESPs is a lower bulk gas temperature by heat transfer from the heated gases to the flowing water (David J. Bayless et al. 2004, 781; Dr. David J. Bayless, John Caine 2001). Based on the Deutsch-Anderson model, the collection efficiency ($\eta$) is still inherently limited in both the dry and wet ESP architectures due to the turbulent exhaust flow. Re-entrainment in the case of dry ESP systems and high bulk gas flow rates in wide channels in either ESP systems, contribute to these turbulent conditions.
The Ohio Coal Research Center (OCRC) at Ohio University has developed a prototype laminar wet-membrane electrostatic precipitator (ESP), designed to maximize the collection efficiency of PM$_{2.5}$ aerosols by maintaining a laminar flow regime (David J. Bayless et al. 2004, 781; Dr. David J. Bayless, John Caine 2001; Ke Li Feb 2005).

To achieve and validate collection efficiency of PM$_{2.5}$, using the current prototype system, some issues must be addressed. In this paper we present strategies to characterize and optimize parameters involved in the LESP operation.

Theoretical considerations and system modifications are described in Chapter 3 and 5, relating to the attainment of laminar flow and flow path optimization in LESP. Entrance length was calculated for predicting the attainment of fully developed flow within the test system. Velocity measurements were performed using pitot tube and air velocity transducer. Visual characterization of flow was performed by using smoke and video recorder.

Different electrode geometry were studied and Voltage-Current (V-I) characteristics plotted to achieve optimal output for field intensity and maximum charging of the particles. Different charging mechanisms are discussed in Chapter 3, for the specific size range of particles.

The injection rate of the solution of sulfuric acid in water was calculated to match the flue gas values and provide that concentration of sulfuric acid, given the volumetric airflow rate and used for aerosol generation. This calculation is explained in Chapter 5.

In addition to matching the concentration, to fully test the efficiency of the wet laminar ESP, the particles generated by the injection system must lie primarily in the
PM$_{2.5}$ range. With limitations described later, particle size was analyzed using the Malvern MASTERSIZER. Techniques that should improve on this approach, for measuring aerosol particle size, are discussed in the recommendations in Chapter 6.

One of the parameters of foremost importance is the temperature gradient in the laboratory system. In the current horizontal prototype, presence of significant vertical temperature gradient through the system is due to buoyancy effects, which is critical. Alternative approaches to minimize the thermal gradient and maintain the desired size of particulates are discussed in Chapter 6.
CHAPTER 2: LITERATURE REVIEW

The past years have seen the development of dry ESPs and movement towards wet ESPs. ESP design depends on the classic Deutsch-Anderson model (Parker 1997). Many parameters have been studied to improve the efficiency. Some of the experiments include study of electrode design, ESP dimensions, collection metal plate versus fiberglass fabric membrane, etc. (Parker 1997; Kim, S. H., Lee, K. W. 1999, 3-25)

To date, the most important design parameters under consideration for the ESP operation has been the charging electrode and the collection membrane. The basic function of the charging electrode is to produce enough ions and electrons (producing better field intensity). Many changes have been seen in the design of the charging electrodes. Some of these modifications were due to the non-durability, instability and poor corona formation, by the electrodes. Electrode design modification is performed to enhance the charging of particles. Mace electrode developed by Dr. Pasic at Ohio University was more stable and produces better field intensity than the current SEI electrode in use (Madan Teegala 2007). A major characteristic of the collection surface is to attract and retain the particles. It should be stable enough to work under the acidity and extreme temperature of flue gas (White 1963). The most common approach in the past was the use of metal plates as a collection surface. However, particles would start accumulating on the surface, thus forming a layer and reducing the electrostatic collection. Further advancement involved a mechanical rapping arrangement for the particulate matter to fall off (White 1963). This arrangement caused some of the particulate matter to re-enter the flow and thus limit the collection efficiency. A recent
approach with the use of wet membranes in the ESP, eliminates corrosion as well as re-entrainment (Dr. David J. Bayless, John Caine 2001; Kim, S. H., Lee, K. W. 1999, 3-25). Modification in the electrode, and collection plates spacing have significant effect on the collection efficiency for any ESP (Chung-Liang Chang and Hsunling Bai 2000, 228-238).

Particle size can have substantial effect on the charging process. Studies (Flagan and Seinfeld 1988; Marquard 2007, 597-610) show that particles smaller than 1μm are charged by diffusion charging, whereas greater than 1μm are charged by field charging. Superimposing the diffusion charging mechanism with an external source (field charging mechanism) helps to achieve better overall charge on the particles (Marquard 2007, 597-610). These fine particles move slowly towards the collection membrane, thus reducing the collection efficiency (See Figure 2.1)

![Figure 2.1: Effect of field charging and diffusion charging on migration velocity, $V_e$, as function of particle diameter, $D_p$ (Flagan and Seinfeld 1988).](image-url)
Past work carried out in the OCRC showed results which were in agreement with the study of field and diffusion charging effects on migration velocity ($V_e$), which is the velocity with which the particles travel towards the collection membrane under influence of electric field (Parker 1997; Hinds 1982). Figures 2.1 can be compared to Figure 2.2 which was calculated following Flagen and Seinfeld approach (Flagan and Seinfeld 1988), with parameters for the current experimental system from the OCRC. From the calculations, when combined charging effect was considered, particles with 0.5 μm diameter were found to travel with a minimum migration velocity of 0.08 m/s. Refer to Appendix A and B for migration velocity calculations performed using Engineering Equation Solver (EES).

![Figure 2.2: Current estimates of field and diffusion charging effects on migration velocity based on past OCRC experimental values.](image)
For laminar flow, theoretical collection efficiency achieves 100% (Hinds 1982). The models predicting the efficiency based on the flow pattern are shown in the following, Figure 2.3.

In the above figure, $V_e$ is the electric migration velocity derived in chapter 3, $A$ is collection surface area, and $Q$ is the volumetric flow rate (Hinds 1982). Collection efficiency decreases as bulk gas velocity increases, as shown by the two extremes of laminar and turbulent in Figure 2.3. Lower bulk gas velocity, increases the residence time.
of particles in the charging region and thus helps them to become fully charged (Kim, S. H., Lee, K. W. 1999, 3-25).

Refer to Appendix C, Engineering Equation Solver (EES) code for efficiency calculations considering uniform particle size of 0.2 μm, combined charging effect and turbulent flow model.

Taking all of these into account, modifications in the regular ESP were made and a novel design was built. The effect of re-entrainment due to rapping was eliminated using the wet membrane technology. The pre-charging section was separated from the main section, which facilitated an increase in residence time of the particles in the field and helped them to acquire maximum charge (David J. Bayless et al. 2004, 781; Dr. David J. Bayless, John Caine 2001). With these proper arrangements, tests were conducted and results obtained. Results showed decrease in collection efficiency with decrease in gas velocity (Ke Li Feb 2005). This should not have been the case. This accounts for many parametric considerations. One of the foremost criteria is the test repeatability under steady conditions. For larger particle size (>1μm) charging is dominated by an external source. Charging of ions in the presence of an electrical field is referred to as “field charging” (see Figure 2.1 and 2.2). As the particle size decreases, field charging effectiveness dwindles. Diffusion charging becomes more effective with reduction in particle size; see Figures 2.1 and 2.2 for illustrations of the relative effects of diffusion charging and field charging on migration velocity (Flagan and Seinfeld 1988). The particle range (PM2.5) to be dealt with is characterized by both field and diffusion charging.
CHAPTER 3: THEORETICAL BACKGROUND

3.1 Prediction models

Prediction models help us evaluate the efficiency of the unit. Various models were developed in the past for analysis which were dependent on the Deutsch model (Parker 1997). Deutsch model applies to turbulent flow. Ideal ESP gas flow is laminar; it gives the particulates enough residence time and a predictable environment to allow capture by the collection membranes (see Figure 2.3 and the following discussion). Figure 2.3 shows the optimal collection resulting from a laminar flow field (Hinds 1982).

Collection efficiency models employed for ESP design based on the flow pattern:

- **Deutsch-Anderson model (Turbulent flow):**
  \[ \eta = 1 - \exp\left(-\frac{V_e A}{Q}\right) \]  
  eq 3.1

- **Laminar model (Laminar flow):**
  \[ \eta = \frac{V_e A}{Q} \]  
  eq 3.2

\(V_e\) is the velocity with which the particles travel towards the collection membrane under influence of electric field and termed as electric migration velocity, \(A\) is collection surface area, and \(Q\) is the volumetric flow rate (Parker 1997; Hinds 1982).

3.1.1 Deutsch model

The Deutsch model is one of the oldest models used to evaluate the efficiency of the ESP unit, considering turbulent flow pattern. It provides the foundation of many other models (Parker 1997).
a. For tubular geometry (Hinds 1982):

As derived by Hinds from “Aerosol Technology”, consider the cross section of an ESP with tubular geometry as shown in Figure 3.1.

Assumptions of Deutsch model:

1. Bulk gas and particles move in horizontal direction at constant velocity.
2. Particles are uniformly distributed in the bulk gas.
3. Electric field strength is uniform.
4. There is no re-entrainment.

Particles move with the electric migration velocity of $V_e$ towards the collection plate.

When particles are within the distance of $V_e dt$, they will be removed.

Considering $N$ as the particle concentration, fraction of particles ($dN / N$) removed will be the negative ratio of annulus area to the total cross sectional area of tube.

$$\frac{dN}{N} = -\frac{2\pi RV_e dt}{\pi R^2} = -\frac{2V_e dt}{R}$$
Integrating from initial concentration of $N_0$ at time $t=0$ to final concentration $N_t$ at time $t$

$$\int_{N_0}^{N_t} \frac{dN}{N} = \int_0^t \frac{2V_e}{R} dt$$

Hence we have:

$$\frac{N_t}{N_0} = \exp\left[-\frac{2V_e t}{R}\right]$$

For tube of length $L$ and volumetric flow rate of $Q$, the residence time in tube $\Pi R^2 L / Q$

can be substituted to find efficiency ($\eta$) as

$$\eta = 1 - \frac{N_t}{N_0} = 1 - \exp\left[-\frac{2\pi V_e R L}{Q}\right] = 1 - \exp\left[-\frac{V_e A}{Q}\right]$$

$A=2 \Pi R L$ which is the collection surface area of the tube.

b. For rectangular geometry:

Consider the rectangular geometry as shown in Figure 3.2.

For rectangular section of length $L$ and volumetric flow rate of $Q$, the residence time in tube $(H \Delta x L) / Q$ can be substituted to find efficiency $\eta$ as
\[ \eta = 1 - \frac{N_t}{N_0} = 1 - \exp \left( - \frac{V_e \cdot H \cdot L}{Q} \right) = 1 - \exp \left( - \frac{V_e A}{Q} \right) \]

\( A = H L \) which is the collection surface area and \( V_e \) is electric migration velocity.

### 3.1.2 Laminar model

Deutsch model represents turbulent flow but the process investigated applies to laminar flow. This results in different equations for the process. If the particles follow laminar streamline in absence of any kind of turbulence, they are unaffected by eddies. There is a feasibility of achieving 100% collection efficiency.

Assumptions of the Laminar Model (Parker 1997; Hinds 1982):

- No driving force for particles in direction opposite to electric field.
- Particles are unaffected by eddies.
- Particles follow laminar streamline.

As derived by Hinds from “Aerosol Technology”, consider a charged particle with charge \( q \) traveling between the electrode and the collecting surface. Distance between surfaces is \( dx \). Force acting on the particle will be

\[ F_E = q \times E \]

\[ E = \text{voltage} / dx \]

The particle moves a maximum distance of \( dx \) in X direction before it can travel a distance of \( L \) (collection surface length) in the Y direction (bulk flow direction) to be collected. Efficiency is defined as the ratio of mean gas residence time in precipitation zone compared to time a particle of size \( D_p \) needs to travel distance \( L \).
\[ \eta = \frac{t_y}{t_x} \]

For smaller particles of size (<25µm), the slip velocity with respect to bulk flow is small (i.e. particle velocity = velocity of gas).

\[ t_x = \frac{dx}{V_x} \quad \text{and} \quad t_y = \frac{L}{V_y} \]

\[ \therefore \eta = \frac{LV_x}{dxV_y} \]

But collection surface area is \( A = L \cdot W \); flow rate is \( Q = W \cdot dx \cdot V_y \); \( V_x \) is the velocity with which the charged particle travels towards the membrane which is “electric migration velocity (\( V_e \))” (Hinds 1982); and \( V_y \) is the downstream velocity in Y direction.

Applying these in the above equation we can deduce,

\[ \eta = \frac{AV_e}{Q} \]  \hspace{1cm} (Equation 3.2)

### 3.2 Electric migration velocity

The particulates are charged in a pre-charging section before commencing entry into and the main section. The oppositely charged metal plate repels the charged particle and forces motion towards the membrane. The velocity with which the charged particle travels towards the membrane is called the “electric migration velocity”. Increasing electric migration velocity by increasing particle charge or field strength also will increase collection efficiency (Hinds 1982). Electric migration velocity is derived by equating the drag force to electrostatic force as in “Aerosol Technology”, W. C. Hinds.
Basis: *Electrostatic force = Drag force*

**Electrostatic force:**

Force on a particle with \( n \) elementary units of charge in field \( E \) will be
\[
F_E = n.e.E
\]

Here, \( e \) is the charge of an electron.

The saturation charge that is reached after sufficient time at a given charging condition:
\[
n_s = \left( \frac{3\varepsilon}{\varepsilon + 2} \right) \left( \frac{ED_p^2}{4eK_e} \right) \tag{eq 3.3}
\]

Here, \( \varepsilon \) is the dielectric constant of the particle (which is relative strength of the electrostatic field produced in different materials by fixed potential) and \( K_e \) is the electrostatic constant and depends on system of units used.

\[
K_e = \frac{1}{4\pi\varepsilon_0} \quad \text{in SI system.}
\]

Here, \( \varepsilon_0 \) represents dielectric constant of vacuum.

\[
\therefore F_E = e \times E \times \left( \frac{3\varepsilon}{\varepsilon + 2} \right) \left( \frac{ED_p^2}{4eK_e} \right)
\]

which is reduced to:
\[
F_E = \left( \frac{3\varepsilon}{\varepsilon + 2} \right) \left( E^2 D_p^2 \varepsilon_0 \pi \right) \tag{eq 3.4}
\]

**Drag force (Hinds 1982):**

Stokes derived the equation for drag when the inertial forces are negligible.

Stokes law is a solution to the Navier-Stokes equation where the fluid was considered incompressible and in steady motion. The velocity at the surface of the particle is zero.
Forces acting at any point in fluid, surrounding spherical particle, in the direction opposite to the particle motion are - normal and tangential force.

As derived by Hinds from “Aerosol Technology”

Normal force \((F_n)\): \(\pi \cdot \mu \cdot V \cdot D_p\)

Tangential force \((F_t)\): \(2\pi \mu V D_p\)

Total resisting force \((F_D)\): \(3\pi \mu V D_p \cdot C_D\)

where, \(C_D\) is the drag coefficient.

*Figure 3.3: Drag coefficient versus Reynolds number for spheres (Hinds 1982).*

The Drag coefficient for the different regions is shown in the Figure 3.3. An important assumption of Stokes law is that the zero fluid velocity at particle surface is unmet for small particles whose size approaches mean free path of gas. When the particle
size is less than 1 µm then this error becomes significant. This was accounted by
Cunningham (1910) who derived the correction factor for Stokes law and hence called it
the Cunningham correction factor $C_c$. This factor reduces the drag force by:

$$F_D = \frac{3\pi \mu V D_p C_D}{C_c} \quad \text{eq 3.5}$$

Here, the Cunningham correction factor will be given by

$$C_c = 1 + \frac{2.52 \lambda}{D_p}$$

and for Stokes

for $\lambda < 0.01 \mu m$

$$C_c = 1 + \lambda \left[ 2.514 + 0.8 \exp \left( -0.55 \frac{D_p}{\lambda} \right) \right]$$

$K_n$ is the Knudsen number and is dimensionless for the interaction of gases and particles.
This is the ratio of mean free path to particle radius, $(K_n = 2\lambda / D_p)$ which reduces the
Cunningham correction factor to:

$$C_c = 1 + K_n \left[ 1.257 + 0.4 \exp \left( -\frac{1.1}{K_n} \right) \right]$$

Equating the two forces we have, $F_E = F_D$ from eq. 3.4 and eq. 3.5

$$\left( \frac{3\varepsilon}{\varepsilon + 2} \right) \left( E^2 D_p^2 \varepsilon_0 \pi \right) = \frac{3\pi \mu V D_p C_D}{C_c}$$

$$\therefore V_e = \frac{C_c E^2 \varepsilon_0 \left( \frac{3\varepsilon}{\varepsilon + 2} \right) D_p}{3\mu C_D} \quad \text{eq 3.6}$$

From the above equation, one can analyze that the electric migration velocity can be
increased by increasing the particle charge. This ultimately affects the collection
efficiency (as seen in equation 3.1 and 3.2).
3.3 Particle charging process

Particles are charged when they are subjected to the electric field. Charging depends on the particle size. There are two dominant types of charging: field and diffusion. Diffusion charging occurs naturally due to the small particle size ($\leq 0.2 \mu m$). And the one due to the electric field applied is field charging. Thus, we can classify the charging as diffusion charging for small particle size and field charging for large particle size. Refer Figures 2.1 and 2.2, which shows the charging employed for various particle sizes (White 1963; Hinds 1982).

3.3.1 Diffusion charging:

Electric field charging is less effective for particles of small size (for particles $\leq 0.2 \mu m$). Random collision between ions and particles causes the particles to get charged. This process is called diffusion charging (White 1963; Flagan and Seinfeld 1988; Hinds 1982).

Thermal energy of the gas molecules is shared by the ions present. Ions diffuse through the gas and collide with particles due to their thermal motion. Electrical forces make the ions adhere to the particles. Ion diffusion provides particle charging which does not depend upon the external electric field (White 1963). The number of charges acquired by particles is given by (Flagan and Seinfeld 1988; Hinds 1982):

$$n = \frac{D_p kT}{2e^2} \ln \left[ 1 + \frac{\pi D_p c_i e^2 N_i t}{2kT} \right]$$

Here, $c_i$ is the mean thermal speed of ions (equal to $2.4 \times 10^4$ cm/sec.) and $N_i$ is concentration of ions.
3.3.2 Field charging

For large particle size ($\geq 0.5 \, \mu m$), charging is carried out by an external source. Charging of ions in presence of strong electric field is called “field charging.” Ions and particles collide with each other due to rapid motion of ions in electric field. Field lines are created due to electric field along which ions travel. Field lines intersect the particles and this is where the ions collide with the particles. They transfer their charge to the particles. The particles thus charged repel the similarly charged incoming ions. This causes the field to alter. Thus, particle is charged to an extent where the field lines and ions deviate. This is saturation point or charge of the particle (White 1963; Hinds 1982)

When diffusion charging is neglected, the number of charges $n$ acquired by particles is (Hinds 1982),

$$n = \left( \frac{3\epsilon}{\epsilon + 2} \right) \left( \frac{ED_p}{4e} \right)^2 \left( \frac{\pi e Z_i N_i t}{1 + \pi e Z_i N_i t} \right)$$

Here, $\epsilon$ is the dielectric constant of particle and $Z_i$ is mobility of ions, approximately 450 cm$^2$/stV.sec. The final term in above equation is time dependent and will be 1 when $\pi e Z_i N_i t >> 1$. Therefore saturation charge $n_s$ will become (Hinds 1982):

$$n_s = \left( \frac{3\epsilon}{\epsilon + 2} \right) \left( \frac{ED_p}{4e} \right)^2$$  eq 3.8

Ion concentration is the only factor which affects the rate of charging. In field charging the ion concentration is $10^7$ cm$^3$ or greater so about 95% charging will be attained in less than 3 seconds (Parker 1997; Hinds 1982).
Figure 3.4: Electric field lines for a conducting particle in a uniform field (a) An uncharged particle. (b) Partially charged particle. (c) Particle at saturation charge (Hinds 1982)
3.4 Introduction to Laminar flow

Attainment of laminar flow is based on the entrance length, \( L_e \), which is defined as the downstream length after which fully developed flow is achieved. Theoretically this is given by the relation (Barber, R. W., Emerson, D. R. 2001; engineeringtoolbox):

\[
L_e = D_h \cdot E_L
\]

\( D_h \) is the hydraulic diameter given by,

\[
D_h = 2 \frac{h_w}{h + w}
\]

Here, \( w \) and \( h \) are width and height, respectively.

\( E_L \) is entrance length number which is function of Reynolds number and given by (Barber, R. W., Emerson, D. R. 2001; engineeringtoolbox).

\[
E_L = \frac{0.315}{0.0175 \cdot R_e + 1} + 0.011 \cdot R_e
\]

However, turbulence also results from non-uniformity in bulk gas flow distribution. Thus, the flow rate should be maintained low enough to increase the residence time by working within the laminar regime and yet at a level, high enough to attain an increased collection efficiency at that point (Dr. David J. Bayless, John Caine 2001; Flagan and Seinfeld 1988)
CHAPTER 4: EXPERIMENTAL SETUP AND TEST PLAN

4.1 Experimental setup

Basic operation of the laminar ESP involves three steps. In the pre-charging section, charging of the particles to be collected via a high-voltage electric discharge is carried out. In the laminar section the particles are collected on the surface of an oppositely charged collection surface. Finally the surface of the collection membrane is cleaned by washing the surface with liquid, rather than mechanically rapping the collection plates (David J. Bayless et al. 2004, 781; Dr. David J. Bayless, John Caine 2001; Ke Li Feb 2005). Figure 4.1 shows the laboratory LESP built for the experimental purpose. Figure 4.2 is the schematic side view of the rig. It identifies the various parts of the unit.

Figure 4.1: Wet Laminar ESP experimental set-up.
Pre-charging section parts:

- Injection system;
- Gas burner;
- Inlet sampling port;
- Transformer rectifiers for pre-charging voltage;
- Pre-charging electrodes (qty. 2) and carbon fiber membranes (qty. 3);

The injection system is designed to inject aerosols in the pre-charging section. The system shown in Figure 4.3a uses a mini pump for suction of sulfuric acid, a port for injecting aerosol particles, and a port for initial sampling. The injection header is designed for uniform distribution of the aerosols generated in the bulk gas (See Figure 4.6). Sulfuric acid is injected in the injection port with a mini pump, which is then evaporated due to the high temperature in the burner and then condensed in the pre-
charging section to generate aerosols (See Figure 4.3b). The diameters of the aerosols generated are measured using the Malvern MASTERSIZER shown in Figure 4.4 (Ke Li Feb 2005)

*Figure 4.3 a:* Injection system for aerosol generation and injection in the system.

*Figure 4.3 b:* Injection system for aerosol generation and injection in the system.
A gas burner was installed to maintain the temperature of the gas at the desired range in order to replicate the flue gases emitted from the power plants. Figure 4.6 shows the burner installed in the pre-charging section. The membranes are designed for optimality. Electrodes shown in Figure 4.5 can achieve high field strength (Ke Li Feb 2005).

Figure 4.5: Membrane (qty 3), Electrodes (qty 2) in Pre-charging section (Ke Li Feb 2005)
Hippotronics transformer rectifiers apply high voltage for the pre-charging section. Inlet sampling ports as shown in Figure 4.7 are provided in the pre-charging section to perform the initial sampling (Ke Li Feb 2005).

*Figure 4.6: Burner, Injection header in Pre-charging section (Ke Li Feb 2005)*

*Figure 4.7: Inlet sampling ports in the pre-charging section.*
Laminar section parts:

- OMNISIL fiber membranes (qty. 9) and metal plates (qty. 8);
- Continuous water feeding system to prevent re-entrainment (a flow meter is installed to observe and regulate the flow of water over the collecting plates);
- Transformer rectifiers for collection plate voltage;
- Induced fan draft;

In the main section there are nine OMNISIL fiber membranes with dimensions of 1’10”×7’6” forming 220 ft² collection surface area. Eight metal plate electrodes are placed between the collection membranes (see Figure 4.8). The distance between the membrane and electrode was 5 cm. Water was drizzled through the membranes. Flow rate of water using the valve arrangement (see Figure 4.9) was adjusted for maintaining uniform film (Ke Li Feb 2005). An exhaust fan was used and with the ‘T’ blower arrangement (see Figure 4.10) the velocity of flow was maintained in the range of 0.2 m/s to 0.8 m/s. A new ‘T’ arrangement has been made for reducing the bulk gas flow. Bulk gas flow was reduced to the desired range by adjusting the blast gate.
Figure 4.8: Omnisil membrane (qty 9) and Metal plates (qty 8) (Ke Li Feb 2005).

Figure 4.9: Water feeding system for wet membrane (Ke Li Feb 2005).
The standard operating procedure was setup for the overall experimentation and followed whenever the unit was operated. Modified EPA method 17 was followed for the isokinetic sampling. Velocity was measured using an air velocity transducer and a pitot tube. An exhaust duct transfers the flue gas to the fume hood.

4.2 Test plan

Current research focuses on optimizing and evaluating various operating parameters involved in LESP operation to enhance the collection efficiency of aerosols. Some of the principle operating conditions which need to be taken into account in order to achieve the objectives, are listed as follows:
• Bulk gas velocity (as set by blast gate adjustment);
• Voltage to pre-charging and laminar section electrodes;
• Sulfuric acid concentration (used for generations of aerosols);
• Particle size distribution analysis;
• Temperature measurements;

These parameters were optimized thereby enhancing the overall collection efficiency of the prototype unit. Standard test matrix for most of the measurements is shown in Figure 4.11. The matrix consists of nine test points as seen from the front view. These test points are accessed through the inlet and outlet ports. A side view in the following figure resembles the inlet and outlet ports through which the test points were accessed.

*Front view*  
*side view*

*Figure 4.11: Test matrix*
CHAPTER 5: RESULTS AND DISCUSSION

5.1 Entrance length calculations

In the laminar section, the height of the membrane and metal plate was approximately 0.6096 m and the distance between the plate and the membrane (width) was approximately 0.0508 m. This formed the parallel plate channel (See Figure 5.1) for the prototype unit.

![Figure 5.1: Downstream parallel plate channel.](image)

Diameter was calculated using the hydraulic diameter formulae (refer to section 3.4 page 33) and found out to be 0.0937 m. Maximum velocity \((V_m)\) was related to average gas velocity \((V_g)\) by the equation \(V_g = \frac{2}{3} V_m\). Considering the viscosity of standard air at 100 °C as \(2.2 \times 10^{-5} \text{ m}^2/\text{s}\), and using the values of hydraulic diameter and viscosity of air, Reynolds number was calculated using \(Re = \frac{V_g D_h}{\nu}\). Using the equation from section 3.4, page 34 for flow through the parallel plate channels, calculations were carried out and entrance length was computed.
Table 5.1

*Entrance length calculations for the prototype unit*

<table>
<thead>
<tr>
<th>Maximum Gas velocity, $V_m$ (m/s)</th>
<th>Average velocity, $V_g$ (m/s)</th>
<th>Reynolds number, $R_e$</th>
<th>Entrance length number, $E_L$</th>
<th>Entrance length, $L_e$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.13</td>
<td>569</td>
<td>6.28</td>
<td>0.59</td>
</tr>
<tr>
<td>0.3</td>
<td>0.20</td>
<td>853</td>
<td>9.4</td>
<td>0.88</td>
</tr>
<tr>
<td>0.4</td>
<td>0.26</td>
<td>1137</td>
<td>12.5</td>
<td>1.17</td>
</tr>
<tr>
<td>0.5</td>
<td>0.33</td>
<td>1421</td>
<td>15.6</td>
<td>1.46</td>
</tr>
<tr>
<td>0.6</td>
<td>0.40</td>
<td>1705</td>
<td>18.7</td>
<td>1.76</td>
</tr>
<tr>
<td>0.7</td>
<td>0.46</td>
<td>1990</td>
<td>21.9</td>
<td>2.05</td>
</tr>
<tr>
<td>0.8</td>
<td>0.53</td>
<td>2273</td>
<td>25.0</td>
<td>2.34</td>
</tr>
<tr>
<td>0.9</td>
<td>0.60</td>
<td>2557</td>
<td>28.1</td>
<td>2.64</td>
</tr>
<tr>
<td>1.0</td>
<td>0.66</td>
<td>2842</td>
<td>31.2</td>
<td>2.93</td>
</tr>
</tbody>
</table>

The length of the laminar section for the prototype unit was approximately 2.4m.

By maintaining the flow below 0.8 m/s there was a possibility of attaining fully developed flow within the test section.
5.2 Velocity profile

Blast gate arrangement maintained the bulk gas velocity in the desired range (refer to section 4.1, Figure 4.10). Blast gate was adjusted to fully open, fully closed or partially open position for various velocity ranges. Velocity was measured in the pre-charging section and main section of the unit using an air velocity transducer and a pitot tube. Velocity in the pre-charging section was measured at the nine test points and an average was calculated based on the measurements. This was the velocity assigned for the bulk gas flow. Measurements were carried out at the centerline, between plates in the laminar section, for blast gate fully open (low velocity) and fully closed (high velocity) near the end of the LESP.

Table 5.2

*Velocity at different blast gate position*

<table>
<thead>
<tr>
<th>Blast gate position</th>
<th>Average gas velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full open</td>
<td>0.2 to 0.5 m/s</td>
</tr>
<tr>
<td>75% open</td>
<td>0.5 to 0.8 m/s</td>
</tr>
<tr>
<td>50% open</td>
<td>0.8 to 1.2 m/s</td>
</tr>
<tr>
<td>Full closed</td>
<td>1.2 to 2.2 m/s</td>
</tr>
</tbody>
</table>

An air velocity transducer was used to measure the velocity between the metal plate and collection membrane. The transducer was inserted in the unit from top to bottom and measurements were taken every 2” down the unit. The velocity measurement
was performed about 1’ from the end of the laminar section. Figure 5.2 shows that there was considerable turbulence at the top and bottom of the unit. This was probably due to the gap between the membrane and the top of the LESP unit. Eddies might have caused turbulence, thus creating an unsteady, irregular velocity profile near the top and bottom. The length of the main section was 2.4 m, which was within the entrance length, calculated to be 2.34 m for 0.8 m/s. This was close to the region where fully developed flow can be obtained. Figure 5.2 shows that the flow with an average velocity of 0.4 m/s was less turbulent than the flow with an average velocity of 2 m/s.

Velocity measurements were carried out at the end of LESP. Vertical centerline point (1’ from the end of laminar section) was selected. Velocity was measured using transducer with the Agilent data unit for recording data over time span of one hour. Measurements were performed twice to verify the stability, and repeatability. Figure 5.3 shows velocity measurements conducted over time span of one hour. The variation in velocity with respect to time was observed to fall within 0.4 ± 0.1 m/s for any particular measurement for one hour. Multiple measurements verified the repeatability associated, which was within ± 0.05 m/s. Average velocity between the multiple readings differed within ± 0.02 m/s. Stability of the exhaust was analyzed by this particular measurement over the time span of one hour.
Figure 5.2: Centerline velocity profile at the end of LESP with blast gate completely open (low average velocity, 0.4m/s) and completely closed (high average velocity, 2m/s).

Denotes turbulence because of gap between the membrane and the rig.

Figure 5.3: Velocity measurements, at an average velocity of 0.4 m/s, taken at the vertical centerline point (1’ from the end of laminar section) over one hour.
5.3 Voltage measurements

Voltage-current (V-I) characteristics had to be determined in order to optimally charge the electrodes. This assists in achieving a stable corona for particle charging (Ke Li Feb 2005). SEI electrodes were in use for applying voltage in the pre-charging section. New electrodes have been developed by Dr. Pasic at Ohio University. These were built up and tested against the SEI electrodes. Mace and Suspended Mace were the two developed electrodes tested. Figure 5.4 shows different electrode configurations (Madan Teegala 2007). Voltage was applied using a Hippotronics transformer-rectifier set to these different electrode geometries, and corresponding current was measured.

Corona and arc voltage captured with a camera during voltage application using suspended mace electrode are shown in Figures 5.5 and 5.6 respectively.

*Figure 5.4: Different electrode geometries (Madan Teegala 2007).*
Figure 5.5: Corona is visible at the tip of suspended Mace electrode.
Figure 5.6: Arc voltage observed during voltage application to suspended Mace electrode.
All three electrodes were tested in the prototype unit with and without the burner in operation. Testing was conducted as passing heated gas through the charging electrodes causes a drastic reduction in the arc voltage. Tables 4.2 and 4.3 demonstrate a comparison using the three electrodes with and without burner in operation for stable and unstable conditions. Results confirm the theoretical assumption of reduction in voltage for heated air. Greater stability of 40 kV (for SEI and Suspended Mace) and 45 kV (for Mace) for longer period was attained. SEI and Suspended Mace were unstable in the range of 40-45 kV whereas Mace was unstable in the range of 45-50 kV. For example, if the voltage of Mace electrode was increased above 45 kV to 50 kV, the voltage tripped off, within a short duration of 5 minutes. But when voltage of 40 kV was applied, it maintained its stability for a longer time.

Table 5.3

<table>
<thead>
<tr>
<th>Electrode type</th>
<th>Voltage only</th>
<th>Burner in operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V (kV)</td>
<td>I (mA)</td>
</tr>
<tr>
<td>SEI Electrodes</td>
<td>40</td>
<td>6</td>
</tr>
<tr>
<td>Suspended Mace</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>Mace</td>
<td>45</td>
<td>10</td>
</tr>
</tbody>
</table>

*VI characteristics for different electrode geometry (Stable operation for longer period)*
Table 5.4

*VI characteristics for different electrode geometry (Unstable operation for time more than five minutes)*

<table>
<thead>
<tr>
<th>Electrode type</th>
<th>Voltage only</th>
<th>Burner in operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V (kV)</td>
<td>I (mA)</td>
</tr>
<tr>
<td>SEI Electrodes</td>
<td>40-45</td>
<td>6</td>
</tr>
<tr>
<td>Suspended Mace</td>
<td>40-45</td>
<td>12</td>
</tr>
<tr>
<td>Mace</td>
<td>45-50</td>
<td>10</td>
</tr>
</tbody>
</table>

Power ($P=VI$) was calculated and power-voltage curves plotted. These are shown in Figure 5.7 and 5.8 for comparison. The results show that the mace and suspended mace electrodes were more efficient than the SEI electrodes when the burner was not in operation (see Figure 5.7). When the electrodes were tested with the burner in operation, there was a considerable reduction in the arc voltage. The reduction does not affect the output of the mace electrode, however. Suspended mace and SEI operate at similar arc voltage whereas the mace electrode operated at higher arc voltage than the other two (see Figure 5.8).
Figure 5.7: Power-voltage characteristic w/o burner operation.

Figure 5.8: Power-voltage characteristic with burner operation.
5.4 Temperature profile

Temperature measurements were performed using the EPA method probe (thermocouple was attached to the probe) and were taken at the nine points as discussed in the test matrix (See Figure 4.11). It was difficult to achieve repeatable heating conditions as the combustion rate varies with the ESP gas flow rate, and the manually-controlled ratio of compressed air and natural gas delivered to the burner. The temperature probe was properly marked for exact positioning in the laboratory setup. Measurements were carried out at the inlet as well as outlet ports. All the measurements were conducted with the blast gate fully opened for maintaining the velocity in the desired range of less than 0.8 m/s. Some tests of different corrective measures were carried out to evaluate their effect on minimizing the vertical thermal gradient.

Solid curve in Figure 5.9 and 5.10 represent the inlet and outlet port temperature measurements respectively, when trial EPA method 17 run was performed. This baseline test with no corrective measures showed a significant vertical temperature gradient, which will not only affect the flow but also the particle size. This will cause uneven dispersion of aerosols in the system, and coagulation thus affecting the particle size. Measurements at the outlet port show reduced temperature due to the effect of heat transfer of gas to water flowing on the collection membrane (Ke Li Feb 2005). Trial runs were carried out to reduce the vertical temperature gradient. For this purpose, the bottom 4” and 6” of the inlet filter was blocked and temperature was measured. Dotted line curve in Figures 5.9 and Figures 5.10 represent the inlet and outlet temperature with 4” blockade. An overhead fan was installed near the injection header to distribute the
thermal gradient towards the bottom of the system. The motor used was as low as 50 CFM in order to avoid turbulence. Broken line in Figures 5.9 and Figures 5.10 represent the inlet and outlet temperature with overhead fan in operation.

With the 4” blockade, no change was evident (See dotted line in Figures 5.9) as compared to those carried out in the trial run of EPA method (See solid line in Figures 5.9). Similar results emerged with the overhead fan in operation (See broken line in Figure 5.9 and 5.10). Heat transfer effect was verified for 4” blockade, as the water system was turned off for the main section. Results showed high temperature at the outlet port for 4” blockade (See dotted line in Figures 5.10) as compared to those of EPA method trial run (See solid line in Figures 5.10).

*Figure 5.9*: Temperature characterization at inlet port

(1 represents trial test, 2 represents overhead fan and 3 represents 4” blockade)
With the 6” blockade, temperature appeared uneven throughout the system (See Figures 5.11 and 5.12). This was due to the burner arrangement in the system. The main burner was installed at the center of the inlet suction. By blocking the bottom 6” of the inlet filter, the bottom portion of the burner operated with an uneven flame, creating uneven heating. Temperature changed continuously as the flame changed direction, forming an uneven flame.

*Figure 5.10*: Temperature characterization at outlet port

(1 represents trial test, 2 represents overhead fan and 3 represents 4” blockade)
Temperature measurement by blocking bottom 6” of the inlet filter

*Figure 5.11*: Temperature characterization at inlet port (with 6” block)

*Figure 5.12*: Temperature characterization at outlet port (with 6” block)
5.5 Aerosol concentration calculation

Acid concentration describes the volume fraction of SO₃ in the flue gas stack, in units of parts per million of flue gas by volume (PPMV) or micrograms per cubic meter (µg/m³). To create conditions similar to the flue gas in a coal-fired stack, a solution of sulfuric acid (H₂SO₄) and water is atomized and injected in the pre-charging section, just past the burner. Based on measurements in full-scale systems, the target concentration is 10 parts of SO₃ per million parts of flue gas, or air, by volume (Environmental Protection Agency; Department of Energy, National Energy Technology Laboratory 2002). This equates to the same PPMV of H₂SO₄ or on a mass basis: 33,500 µg of H₂SO₄ per cubic meter of air.

Assuming flue gas temperature around 100°C at standard pressure, number of moles of flue gas was computed using the Ideal Gas Law. Product of number of moles of flue gas and target concentration of SO₃ was converted into equivalent amount of H₂SO₄ concentration on a mass basis. This calculation is represented in Table 5.5.

Accordingly solution concentration of sulfuric acid in water was computed for generating aerosols in the LESP system, given the volumetric air flow rate and tabulated in Appendix D.
Table 5.5

*Target concentration of sulfuric acid to be used:*

<table>
<thead>
<tr>
<th>Atmospheric pressure</th>
<th>P</th>
<th>101000.00 Pa</th>
<th>Standard value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>T</td>
<td>380 K</td>
<td>Operating condition</td>
</tr>
<tr>
<td>Gas constant</td>
<td>R</td>
<td>8.314 J / K*mol</td>
<td>Standard value</td>
</tr>
<tr>
<td>Volume</td>
<td>V</td>
<td>1 m³</td>
<td>Standard value</td>
</tr>
<tr>
<td>Number of moles</td>
<td>n</td>
<td>31.97 mol flue gas</td>
<td>P V = n R T (Ideal gas law)</td>
</tr>
<tr>
<td>Parts Per Million</td>
<td>PPMV of SO₃</td>
<td>10.7 PPMV</td>
<td>Target concentration</td>
</tr>
<tr>
<td>Molarity</td>
<td>N (H₂SO₄)</td>
<td>0.0003421 mol SO₃</td>
<td>$\frac{n \cdot PPMV}{10^6}$</td>
</tr>
<tr>
<td>Concentration</td>
<td>M (H₂SO₄)</td>
<td>0.0335 g H₂SO₄/m³ flue gas</td>
<td>$33,500 \mu g/m³$</td>
</tr>
</tbody>
</table>
5.6 Particle size analysis

A particle distribution analysis was carried out using the Malvern unit for determining the particle size of the aerosols generated. This was done by injecting the acid of desired concentration through the injection system (Ke Li Feb 2005). Standard test matrix was used for measurements (See Figure 4.11). A glass probe (about 5’ long) masked with proper heating tapes and coupled with the EPA method meter box was used at the inlet ports to sample the aerosols through the Malvern unit. The coupling was done to achieve isokinetic sampling. Heating tape was used to sample the aerosols at the system temperature of 100°C. MASTERSIZER was unable to operate at 100°C. Consequently, the temperature of the glass probe was gradually decreased, to check the operating temperature of MASTERSIZER. It was observed that the equipment only operated at temperatures below 50°C. Experiments were also performed very close to the injection header of the unit. This ensured the sampling distance remained as short as possible.

The first set of analysis was conducted with the heating tape on the glass probe, maintained at 50 °C and with the main burner in operation at the inlet sampling ports. This showed the particle size to be distributed around 1000 μm. Another set of results was obtained with similar operating conditions as of the first set but without the heating tape on the glass probe. Both the results were of the same nature with particle size ranging from 1000 μm to 3000 μm. Figure 5.13 and 5.14 show the results obtained from the Malvern analysis. The measurements were performed at the inlet ports far away from the injection header and the aerosols were sampled at lower temperature. There is a high
probability that the particles might have coagulated before entering the MASTERSIZER. Another concern would be the volume of aerosol sampled. Lower volumes of 2.5 μm aerosols would not be analyzed by the MASTERSIZER.

Another set of experiments was carried out with the Malvern inside the fence and using the first 3’ of the glass probe. This was done to reduce the path length of the sample into the Malvern inlet. Figure 5.15 shows results obtained from the Malvern analysis. In this case, the main burner and the heating tape were not utilized. There was shift of particle size from 1000 μm to around 20 μm. This can be attributed to the short sampling distance.

In yet another example of further reducing the sampling distance, an even smaller glass tube was used with a glass nozzle. The tube was positioned about 3” from the injection header. Figure 5.16 shows analysis obtained from Malvern with burner off and without heating tape. There was gradual shift of particle size distribution to around 1 μm, as compared to the previous two analyses.

The particle size increased due to a decrease in temperature. Cold conditions allow coagulation of particles and, thus there was increase in the particle size. The temperature of the gas was to be maintained above dew point of water. This was done in order to avoid the coagulation of moisture with the aerosols generated (Ke Li Feb 2005). Another factor that was seen to affect the distribution was the sampling distance.
Figure 5.13: Malvern analysis, with burner on, glass probe with heating tape, at the inlet sampling ports
Figure 5.14: Malvern analysis, with burner on, glass probe without heating tape, at the inlet sampling ports
Figure 5.15: Malvern analysis, with burner off, glass probe without heating tape, near the injection header
Figure 5.16: Malvern analysis, with burner off, small glass probe with nozzle, without heating tape, near the injection header
5.7 Flow characterization

Visual flow characterization was performed by passing smoke through the system and then recording the flow through a video recorder. A smoke generator was used to inject the smoke to the inlet via the filter. This was done to see the effect of the overhead fan installed in the pre-charging section. The smoke was seen to be drawn towards the overhead fan and not away from it as was expected. Even after changing the polarity of the fan, the same event occurred.
CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The objective of the present work is to evaluate and enhance the operating parameters in order to enhance the collection efficiency of the wet laminar ESP. Some operating parameters have been analyzed which affected LESP operation. The key findings are discussed next.

In order to enhance possible collection efficiency by producing more laminar flow, velocity of the gas flow in the LESP was reduced using a blast gate arrangement. Velocity measurements indicated considerable amount of turbulence at higher average velocity (2 m/s) as compared to the lower average velocities (0.4 m/s). Also the influence of the building exhaust system was tested and found to have an effect of ± 0.1 m/s. The top and bottom wall of the unit had enough turbulence caused by the gaps between the membranes and the extreme walls (top and bottom) and the uncovered mounting hardware. For reducing the turbulence in the system and producing a better laminar flow, the unit has to be operated at lower velocities. Also the gaps mentioned should be blocked in order to avoid eddy formation and reduce turbulence. With these changes, uniform fully developed laminar flow can be produced thus enhancing the collection efficiency (Dr. David J. Bayless, John Caine 2001).

In order to determine potential entrance effects on laminar flow condition, entrance length was found out to be 2.3 m when maintaining the velocity less than 0.8 m/s, which kept the Reynolds number below 2200, well within the laminar region. It is at this point where fully developed flow can be attained. However, the length of main
section is 2.4 m, indicating that fully developed flow is just possible, but for such a short length that 100% collection efficiency in the LESP would not be likely. So increasing the length of collection section will give more space for producing fully developed flow and it is at this point where theoretically 100% collection efficiency is possible (Dr. David J. Bayless, John Caine 2001).

Electrode power is known to strongly affect charging and collection efficiency. SEI, Suspended Mace and Mace electrodes have been tested for performance. The Mace electrode was found to produce a more stable corona and operate at higher arc voltage as compared to the SEI and Suspended Mace electrodes. Use of better design of electrode would increase the field intensity thus increasing the charge on the particles (Madan Teegala 2007). This will in turn help the particle collection in the collection section.

Vertical thermal gradients have been detected through temperature measurements. This thermal gradient is due to the buoyancy effect. The temperature of the gas should be high enough, to avoid coagulation of acid aerosols. Also it should be uniform throughout the system for uniform generation and distribution of acid aerosols in the system (Environmental Protection Agency; Department of Energy, National Energy Technology Laboratory 2002). It was difficult to achieve repeatable heating conditions as the combustion rate varies with the ESP gas flow rate, and the manually-controlled ratio of compressed air and natural gas delivered to the burner. Temperature measurements were taken using 4” or 6” blockade at the inlet filter. In an attempt to force more even heating of the inlet gases, measurements were also taken by installing and operating an overhead fan near the injection header. The 4” filter blockade and the overhead fan near the
injection header did not reduce the thermal gradient. Thermal measurements with the 6” filter blockade show uneven temperature distribution throughout the system, due to formation of an uneven flame at the burner.

Smoke was generated and passed through the inlet filter into the system for flow visualization to illustrate the operation of the overhead fan, which was used in an attempt to reduce the vertical thermal gradient. The fan drew the smoke towards the fan, not away from it. Therefore, the use of an overhead fan has not been effective as currently configured, for reducing the thermal gradient.

A Malvern MASTERSIZER is used for particle size analysis of sulfuric acid aerosols in the gas stream. Several problems with this technique were found. First, the Malvern had a temperature limitation restricting operation to below 50°C. Second, particle size distribution results were inconsistent. Analyses were conducted at the inlet port using 5’ probe and near the injection header using 6” probe. Results using the 5’ probe contrasted with what was expected. Mean particle size with the 5” probe was found to be around 1000 μm. The analysis using the 6” probe produced some repeatable results showing particles distributed around 1 μm. The 5’ probe results indicated coagulation of particles or condensation of water around the sulfuric acid aerosol with longer sampling distance. The use of shorter probe and sampling close to injection header reduced these effects and produced a more expected particle size analysis.
6.2 Recommendations

The following recommendations are presented to improve experimental operation, improve collection efficiency, and facilitate the collection of data for future research. These recommendations range from increasing the collection section length, installing baffles, changing the electrode design, minimizing vertical thermal gradient using mixing systems, reducing turbulence using flow straighteners, and use of proper particle size analysis equipment such as the TSI SMPS™.

The first recommendation is to increase the collection section length to facilitate laminar flow. By further increasing the length of the main section (or reducing the hydraulic diameter), fully developed laminar flow can be achieved, and residence time of the particles in the test section can be increased thus optimizing the collection efficiency (David J. Bayless et al. 2004, 781; Dr. David J. Bayless, John Caine 2001). The main collecting section of the prototype unit is about 2.4 m long. Entrance length, where fully developed flow can be obtained, was computed to be 2.34 m for the current minimum centerline velocity 0.8 m/s. Therefore, a longer main collecting section would help create a fully developed laminar profile following the turbulent charging section. In addition, a longer collecting section also increases the residence time of the charged particles which in turn enhances the collection efficiency (Dr. David J. Bayless, John Caine 2001).

The next recommendation is to install OMNISIL baffles for blocking gaps where particles may pass uncharged. In the pre-charging section, there are considerable gaps (of 20 cm) on each side between the outer membranes and wall. Particles entering in this exterior region will pass uncharged, making collection difficult. Similar gaps occur
within the laminar section. Even if the particles are charged in the pre-charging section, there is high probability that these particles might enter the exterior region in the laminar section. These particles will not be captured in the laminar section and thus will escape out to the environment.

A proposed modification to minimize these exterior regions is a construction of OMNISIL baffles as shown in the Figure 6.1. This will block the particles from entering in this non-performing region. OMNISIL can operate at high temperature, is acid resistant and thus is safe and effective to use even in the extreme conditions of pre-charging section (Dr. David J. Bayless, John Caine 2001). A limitation of this arrangement is the positioning at the inlet port between the pre-charging section and the laminar section. This arrangement makes the sampling difficult. Proper arrangements should be implemented to make the inlet points accessible before installing.

*Figure 6.1:* Proposed OMNISIL baffle arrangement to reduce escape of aerosols near the walls of prototype unit.
Significant turbulence was observed at the top and bottom wall of the unit, caused by the gaps between the membranes and the extreme walls (top and bottom) and the uncovered mounting hardware. These gaps facilitate the eddy formation as well as provide an additional exterior, non-performing region allowing particles to escape collection. Installation of OMNISIL membranes that can act as top and bottom wall will reduce exposure to these turbulence initiators and limit the number of particles that escape. This kind of baffle arrangement can prevent particles from entering in these exterior non-performing regions and help in achieving better collection efficiency.

The next recommendation is to improve electrode design for better field intensity. SEI electrodes in use were found to operate at a voltage of 40kV, with power up to 70 Watts. Use of electrodes that can produce higher field intensity in the system will help in maximizing charge on the particles. Use of electrodes like Mace will help in generating better corona and enhance the particle charging mechanism (Dr. David J. Bayless, John Caine 2001). Once these particles are charged properly in the pre-charging section, they can be collected more efficiently in the laminar section.

Some electrodes like the Mace (see Figure 6.2), designed and developed by Dr. Pasic at Ohio University, are more stable and produce better corona than the current SEI electrodes in use. Mace electrodes were found to operate at voltages in range of 45kV to 50kV in the charging section. Mace electrodes have multiple corona points and are less expensive than the SEI. Mace electrodes can be easily built and materials used are readily available (Madan Teegala 2007). Vertical positioning of the unit provides enough area to
increase the length of the electrodes along the direction of the flow. Longer electrodes will create larger electric field intensity area for maximizing particle charging.

Figure 6.2: Mace electrode (Madan Teegala 2007).

The next recommendation is to minimize the vertical thermal gradient. Temperature measurements indicated the presence of vertical thermal gradient in the system. Elevating and maintaining the bulk gas temperature to near 100°C to 120°C uniformly throughout the system is important, to prevent condensation of water vapor on the injected sulfuric acid aerosols, and thus to prevent growth of the aerosol particle diameter beyond the desired PM$_{2.5}$ and achieve uniform dispersion of particles vertically across the test section (Madan Teegala 2007).

One approach to achieve the proper temperature distribution is the installation of heating mats, coils and/or pads along the bottom of the unit. These mats are composed of different materials and are readily available (for example: McMaster-Carr has
“Heavy Duty Silicone Rubber Heat Sheets”). A limitation on this approach for the system is that the test section where the mats would go is currently made of Lexan, which has a low temperature limit (< 150°C). Significant deformation has already occurred due to heat transfer from the burner and the impact of any heat source must be considered.

Different mixing systems may reduce the thermal gradient. An additional smaller burner could be installed in the pre-charging section near the bottom to heat the cold air at the bottom. However, the buoyancy effect can still be significant due to the underlying system structure – that is, the current horizontal positioning of the setup.

Another approach could be to change the system to a vertical flow precipitator. This will save laboratory floor space but require a special multi-story laboratory space to accommodate the vertical dimension of about 3 m or more.

These modifications could help eliminate the thermal gradient in both the pre-charging section and the main section, and thus achieve more stable and realistic aerosol size and improve uniform dispersion in the system.

Another recommendation would be to implement techniques to reduce system turbulence. By implementing some of the modifications to reduce the thermal gradient, specifically the use of a mixing fan, turbulence will increase in the pre-charging section. Turbulence in turn will affect the collection efficiency.

Turbulence can be reduced by using different flow straighteners. Flow straightening tubes, vanes, or fins are available and could be installed in an extended pre-charging section to mitigate the turbulence. The flow can thus be guided into the main section for attaining laminar flow and thus enhancing the collection efficiency.
Another recommendation would be to improve the particle size analysis equipment. To determine the efficiency of the wet laminar ESP for collecting PM$_{2.5}$, the size of the aerosols generated in the pre-charging section requires verification. Previously, this verification was done using a Malvern MASTERSIZER. This equipment is designed for ambient temperature, dry powder measurements, though, not elevated temperature aerosols (Malvern). With significant modifications, this equipment was used to measure the aerosol diameter. The Malvern, however, was found to be non-operating for temperature greater than 50 °C. At this lowered temperature, coagulation of aerosols occurs. The sampling distance, from the LESP to the Malvern should be as short as possible. This requires a short sampling probe, and sampling needs to be conducted very close to the injection header. Malvern sells additional equipment, the SPRAYTECH™, built specifically to measure droplets and aerosols that should be suitable for these measurements.

Alternatively, a TSI Scanning Mobility Particle Scanner™ (SMPS), also owned by Ohio University, could be used. This unit consists of an electrostatic classifier and a particle counter. This equipment is designed specifically for aerosols. It uses a continuous and fast scanning mechanism. This helps in avoiding any gaps during the particle size analysis. This equipment uses radioactive material, Krypton 85 (kr-85), a radioactive source (TSI Incorporated). As kr-85 is carcinogenic, the operator must be appropriately trained. The operating conditions of the LESP unit (temperature in range of about 100 °C to 120 °C and use of sulfuric acid) will require controlled dilution to avoid damage to the
system and prevent coagulation. TSI sells a Dilution Bridge (Part# 1050001) that may be suitable (TSI Incorporated). With these precautions damage should not occur.
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http://www.epa.gov/tri/TWebHelp/WebHelp/sulfuric_section_3_1_5_sulfuric_acid_aerosol_formation_in_stacks_from_combustion_processes.htm.


Madan Teegala. 2007. Cost effective corona discharge.


APPENDIX A: CHARGE USING DIFFUSION CHARGING

The code is developed for Engineering Equation Solver (EES). This program is calculates the electric migration velocity, $V_e$, of particles ranging from 0.2 μm to 1 μm. Considering only the diffusion charging effect and using the values of ion concentration, electric field intensity, residence time (from Flagen and Seinfeld) and other standard values, we calculate the electric migration velocity corresponding to the specific particle size. The values generated were used to plot the charging effects on different particle size shown in Figure 2.2.

\[
\begin{align*}
Dp[1] &= 0.2E-6 & \text{(diameter of particle)} \\
Dp[2] &= 0.4E-6 \\
Dp[3] &= 0.6E-6 \\
Dp[4] &= 0.8E-6 \\
Dp[5] &= 1E-6 \\
Temp &= 293 & \text{(temperature)} \\
e &= 1.6E-19 & \text{(charge on an electron)} \\
ci &= 218 & \text{(mean thermal speed of ions)} \\
Zi &= 1.4E-4 & \text{(mobility)} \\
k &= 1.38E-23 & \text{(boltzmann constant)} \\
Dcv &= 8.85E-12 & \text{(Field strength)} \\
strength &= 2E5 & \text{(ion density)} \\
Ni &= 10E13 & \text{(residence time)} \\
t &= 1 \\
\end{align*}
\]

\[
\begin{align*}
n[1] &= ((2\pi*Dcv*Dp[1]*k*Temp)/(e*e))*\ln(1+((Dp[1]*ci*e*e*Ni*t)/(8*Dcv*k*Temp))) \\
n[2] &= ((2\pi*Dcv*Dp[2]*k*Temp)/(e*e))*\ln(1+((Dp[2]*ci*e*e*Ni*t)/(8*Dcv*k*Temp))) \\
n[3] &= ((2\pi*Dcv*Dp[3]*k*Temp)/(e*e))*\ln(1+((Dp[3]*ci*e*e*Ni*t)/(8*Dcv*k*Temp))) \\
n[4] &= ((2\pi*Dcv*Dp[4]*k*Temp)/(e*e))*\ln(1+((Dp[4]*ci*e*e*Ni*t)/(8*Dcv*k*Temp))) \\
n[5] &= ((2\pi*Dcv*Dp[5]*k*Temp)/(e*e))*\ln(1+((Dp[5]*ci*e*e*Ni*t)/(8*Dcv*k*Temp)))
\end{align*}
\]
P=101325                   \{\text{Gas pressure}\}
R=8314                   \{\text{Gas constant}\}
gasmw=0.06*44\{\text{CO}_2\}+0.78*28\{\text{N}_2\}+0.16*32\{\text{O}_2\}          \{\text{Gas molecular weight}\}
rhog=P*\text{gasmw}/(R*\text{Temp})       \{\text{Gas density}\}
mug=\text{viscosity(air,t=Temp)}            \{\text{viscosity}\}
mfp=1.46E-8                \{\text{mean free path}\}

\{\text{Cunningham correction factor for discontinuity}\}
Cc[1]=(1+2.52*\text{mfp}/Dp[1])
Cc[2]=(1+2.52*\text{mfp}/Dp[2])
Cc[3]=(1+2.52*\text{mfp}/Dp[3])
Cc[4]=(1+2.52*\text{mfp}/Dp[4])
Cc[5]=(1+2.52*\text{mfp}/Dp[5])

\{\text{electrical migration velocity}\}
ve[1]=(Cc[1]*n[1]*e*strength)/(3*pi*Dp[1]*mug*(1+0.15*(Re[1]^0.687)))
ve[2]=(Cc[2]*n[2]*e*strength)/(3*pi*Dp[2]*mug*(1+0.15*(Re[2]^0.687)))
ve[3]=(Cc[3]*n[3]*e*strength)/(3*pi*Dp[3]*mug*(1+0.15*(Re[3]^0.687)))
ve[4]=(Cc[4]*n[4]*e*strength)/(3*pi*Dp[4]*mug*(1+0.15*(Re[4]^0.687)))
ve[5]=(Cc[5]*n[5]*e*strength)/(3*pi*Dp[5]*mug*(1+0.15*(Re[5]^0.687)))

\{\text{Reynolds number based on electrical migration velocity}\}
Re[1]=rhog*ve[1]*Dp[1]/mug
APPENDIX B: CHARGE USING FIELD CHARGING

The code is developed for Engineering Equation Solver (EES). This program calculates the electric migration velocity, $V_e$, of particles ranging from 0.2 μm to 1 μm.

Considering only the field charging effect and using the values of ion concentration, electric field intensity, residence time (from Flagen and Seinfeld) and other standard values, we calculate the electric migration velocity corresponding to the specific particle size. The values generated were used to plot the charging effects on different particle size shown in Figure 2.2.

{diameter of particle}
Dp[1]=0.2E-6
Dp[2]=0.4E-6
Dp[3]=0.6E-6
Dp[4]=0.8E-6
Dp[5]=1E-6

Temp=293
{temperature}
e=1.6E-19
{charge on an electron}
ci=218
{mean thermal speed of ions}
Zi=1.4E-4
{mobility}
k=1.38E-23
{boltzmann constant}
Dcv=8.85E-12
{dielectric constant}
dielectric=1
strength=2E5
{field strength}
Ni=1E13
{ion density}

{charge acquired using formulae from flagan & seinfeld}
n[1]=((3*dielectric)/(dielectric+2))*(strength*Dp[1]*Dp[1]*3.14*Dcv)/e

P=101325
{Gas pressure}
R=8314
{Gas constant}
gasmw=0.06*44\{CO2\}+0.78*28\{N2\}+0.16*32\{O2\}
{Gas molecular weight}
rhog = P * gasmw / (R * Temp) \quad \{ \text{Gas density} \}
mug = \text{viscosity(air, } t=\text{Temp}) \quad \{ \text{viscosity} \}
mfp = 1.46E-8 \quad \{ \text{mean free path for gas particles} \}

\{ \text{Cunningham correction factor for discontinuity} \}
Cc[1] = (1 + 2.52 * mfp / Dp[1])
Cc[2] = (1 + 2.52 * mfp / Dp[2])
Cc[3] = (1 + 2.52 * mfp / Dp[3])
Cc[4] = (1 + 2.52 * mfp / Dp[4])
Cc[5] = (1 + 2.52 * mfp / Dp[5])

\{ \text{electrical migration velocity} \}

\{ \text{Reynolds number based on electrical migration velocity} \}
APPENDIX C: PREDICTION OF EFFICIENCY USING COMBINED CHARGING EFFECT

The code is developed for Engineering Equation Solver (EES). This program calculates the efficiency of the LESP unit considering the particle size to be 0.2 μm.

Combined charging effect is being considered (diffusion charging, Appendix A, and field charging, Appendix B). Universal standard values and system values are used as mentioned in the code. Efficiency is calculated and output generated is shown at the end of the program code.

\{velocity of gas\}
vg[1]=0.2
vg[2]=0.4
vg[3]=0.6
vg[4]=0.8
vg[5]=1

I=5.8E-3 \quad \{current\}
V=40000 \quad \{voltage\}
Dp=0.2E-6 \quad \{diameter of particle\}
Temp=393 \quad \{temperature\}
L=0.2286 \quad \{length of membrane\}
h=0.5334 \quad \{height of membrane\}
e=1.6E-19 \quad \{charge on an electron\}
ci=2.4E2 \quad \{mean thermal speed of ions\}
Zi=2E-4 \quad \{mobility\}
deltax=0.1016 \quad \{spacing between membrane and electrode\}
k=1.38E-23 \quad \{boltzmann constant\}
Dev=8.85E-12 \quad \{field strength\}
dielectric=1000 \quad \{area of membrane\}
strength=V/deltax \quad \{ion density\}
A=h*L
Ni=I/(4*A*strength*e*Zi)

\{residence time\}
t[1]=L/vg[1]
\( t[3] = \frac{L}{vg[3]} \)
\( t[4] = \frac{L}{vg[4]} \)
\( t[5] = \frac{L}{vg[5]} \)

{charge acquired using formulae from flagan & seinfeld for field charging}

\[
\begin{align*}
q_f[1] &= \left( \frac{3 \times \text{dielectric}}{\text{dielectric} + 2} \right) \times (\text{strength} \times D_p \times D_p \times 3.14 \times D_{cv}) \\
q_f[2] &= \left( \frac{3 \times \text{dielectric}}{\text{dielectric} + 2} \right) \times (\text{strength} \times D_p \times D_p \times 3.14 \times D_{cv}) \\
q_f[3] &= \left( \frac{3 \times \text{dielectric}}{\text{dielectric} + 2} \right) \times (\text{strength} \times D_p \times D_p \times 3.14 \times D_{cv}) \\
q_f[4] &= \left( \frac{3 \times \text{dielectric}}{\text{dielectric} + 2} \right) \times (\text{strength} \times D_p \times D_p \times 3.14 \times D_{cv}) \\
q_f[5] &= \left( \frac{3 \times \text{dielectric}}{\text{dielectric} + 2} \right) \times (\text{strength} \times D_p \times D_p \times 3.14 \times D_{cv})
\end{align*}
\]

{charge acquired for diffusion charging}

\[
\begin{align*}
q_d[1] &= \left( \frac{2 \times \pi \times D_{cv} \times D_p \times \text{k} \times \text{Temp}}{e} \right) \times \ln(1 + ((D_p \times c_i \times e \times e \times N_{i} \times t[1]) / (8 \times D_{cv} \times k \times \text{Temp}))) \\
q_d[2] &= \left( \frac{2 \times \pi \times D_{cv} \times D_p \times \text{k} \times \text{Temp}}{e} \right) \times \ln(1 + ((D_p \times c_i \times e \times e \times N_{i} \times t[2]) / (8 \times D_{cv} \times k \times \text{Temp}))) \\
q_d[3] &= \left( \frac{2 \times \pi \times D_{cv} \times D_p \times \text{k} \times \text{Temp}}{e} \right) \times \ln(1 + ((D_p \times c_i \times e \times e \times N_{i} \times t[3]) / (8 \times D_{cv} \times k \times \text{Temp}))) \\
q_d[4] &= \left( \frac{2 \times \pi \times D_{cv} \times D_p \times \text{k} \times \text{Temp}}{e} \right) \times \ln(1 + ((D_p \times c_i \times e \times e \times N_{i} \times t[4]) / (8 \times D_{cv} \times k \times \text{Temp}))) \\
q_d[5] &= \left( \frac{2 \times \pi \times D_{cv} \times D_p \times \text{k} \times \text{Temp}}{e} \right) \times \ln(1 + ((D_p \times c_i \times e \times e \times N_{i} \times t[5]) / (8 \times D_{cv} \times k \times \text{Temp})))
\end{align*}
\]

{combined charging}

\[
\begin{align*}
\end{align*}
\]

\[
\begin{align*}
P &= 101325 & \{\text{Gas pressure}\} \\
R &= 8314 & \{\text{Gas constant}\} \\
\text{Temp}_{\text{main}} &= 358 & \{\text{temperature of gas in main section}\} \\
\text{gasmw} &= 0.06 \times 44 \{\text{CO2}\} + 0.78 \times 28 \{\text{N2}\} + 0.16 \times 32 \{\text{O2}\} & \{\text{Gas molecular weight}\} \\
\rho_g &= P \times \text{gasmw} / (R \times \text{Temp}_{\text{main}}) & \{\text{Gas density}\} \\
V_{\text{main}} &= 10000 & \{\text{Voltage in main}\} \\
deltax_{\text{main}} &= 0.03 & \{\text{spacing between membranes in main section}\} \\
\mu_g &= \text{viscosity(air,t=Temp}_{\text{main}}) & \{\text{viscosity}\} \\
\text{strength}_{\text{main}} &= V_{\text{main}} / \text{deltax}_{\text{main}} & \{\text{Electric field strength in main section}\} \\
\text{mfp} &= \mu_g / (0.499 \times P \times (8 \times \text{gasmw} / (\pi \times \text{Temp}_{\text{main}} \times R))^0.5) & \{\text{mean free path for gas particles}\} \\
\text{Cc} &= (1 + 2.52 \times \text{mfp} / D_p) & \{\text{Cunningham correction factor for discontinuity}\}
\end{align*}
\]

{electrical migration velocity}

\[
\begin{align*}
\text{ve}[1] &= (\text{Cc} \times q_f[1] \times \text{strength}_{\text{main}}) / (3 \times \pi \times D_p \times \mu_g \times (1 + 0.15 \times \text{Re}[1]^{0.687})) \\
\text{ve}[2] &= (\text{Cc} \times q_f[2] \times \text{strength}_{\text{main}}) / (3 \times \pi \times D_p \times \mu_g \times (1 + 0.15 \times \text{Re}[1]^{0.687})) \\
\text{ve}[3] &= (\text{Cc} \times q_f[3] \times \text{strength}_{\text{main}}) / (3 \times \pi \times D_p \times \mu_g \times (1 + 0.15 \times \text{Re}[1]^{0.687})) \\
\text{ve}[4] &= (\text{Cc} \times q_f[4] \times \text{strength}_{\text{main}}) / (3 \times \pi \times D_p \times \mu_g \times (1 + 0.15 \times \text{Re}[1]^{0.687})) \\
\text{ve}[5] &= (\text{Cc} \times q_f[5] \times \text{strength}_{\text{main}}) / (3 \times \pi \times D_p \times \mu_g \times (1 + 0.15 \times \text{Re}[1]^{0.687}))
\end{align*}
\]
{Reynolds number correction factor}
\[X[1] = (1 + 0.15 \times Re[1]^{0.687})\]
\[X[2] = (1 + 0.15 \times Re[2]^{0.687})\]
\[X[3] = (1 + 0.15 \times Re[3]^{0.687})\]
\[X[4] = (1 + 0.15 \times Re[4]^{0.687})\]
\[X[5] = (1 + 0.15 \times Re[5]^{0.687})\]

{Reynolds number based on electrical migration velocity}
\[Re[1] = \rho_g \times ve[1] \times D_p / \mu_g\]
\[Re[2] = \rho_g \times ve[2] \times D_p / \mu_g\]
\[Re[3] = \rho_g \times ve[3] \times D_p / \mu_g\]
\[Re[4] = \rho_g \times ve[4] \times D_p / \mu_g\]
\[Re[5] = \rho_g \times ve[5] \times D_p / \mu_g\]

\[\text{Leng} = 2.286\]
\[\text{height} = 0.5588\]

\[\text{residencetime}[1] = \text{Leng} / \text{vg}[1]\]
\[\text{residencetime}[2] = \text{Leng} / \text{vg}[2]\]
\[\text{residencetime}[3] = \text{Leng} / \text{vg}[3]\]
\[\text{residencetime}[4] = \text{Leng} / \text{vg}[4]\]
\[\text{residencetime}[5] = \text{Leng} / \text{vg}[5]\]

{Volumetric flow rate m3/sec}
\[Q[1] = (\text{Leng} / \text{residencetime}[1]) \times \text{height} \times \text{leng}\]
\[Q[2] = (\text{Leng} / \text{residencetime}[2]) \times \text{height} \times \text{leng}\]
\[Q[3] = (\text{Leng} / \text{residencetime}[3]) \times \text{height} \times \text{leng}\]
\[Q[4] = (\text{Leng} / \text{residencetime}[4]) \times \text{height} \times \text{leng}\]
\[Q[5] = (\text{Leng} / \text{residencetime}[5]) \times \text{height} \times \text{leng}\]

\[\text{Area} = 20.32\]

{De=(veA)/Q, nondimensional ratio of volumetric flow to collection membrane divided by bulk volumetric flow rate}
\[D_e[1] = \text{Area} \times ve[1] / Q[1]\]
\[D_e[3] = \text{Area} \times ve[3] / Q[3]\]
\[D_e[5] = \text{Area} \times ve[5] / Q[5]\]
{Theoretical collection efficiency}
\[ n_{\text{theory}}[1] = 1 - \exp(-De[1]) \]
\[ n_{\text{theory}}[2] = 1 - \exp(-De[2]) \]
\[ n_{\text{theory}}[3] = 1 - \exp(-De[3]) \]
\[ n_{\text{theory}}[4] = 1 - \exp(-De[4]) \]
\[ n_{\text{theory}}[5] = 1 - \exp(-De[5]) \]

**OUTPUT:**

<table>
<thead>
<tr>
<th>vg[i]</th>
<th>De[i]</th>
<th>n_theory[i]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>5.957</td>
<td>0.9974</td>
</tr>
<tr>
<td>0.4</td>
<td>2.801</td>
<td>0.9392</td>
</tr>
<tr>
<td>0.6</td>
<td>1.798</td>
<td>0.8344</td>
</tr>
<tr>
<td>0.8</td>
<td>1.312</td>
<td>0.7307</td>
</tr>
<tr>
<td>1</td>
<td>1.027</td>
<td>0.6418</td>
</tr>
</tbody>
</table>
Appendix D: Acid Concentration Calculation for Aerosol Generation in the LESP System

Standard emission (10-20 PPMV) of sulfuric acid aerosols (Environmental Protection Agency; Department of Energy, National Energy Technology Laboratory 2002) is considered for calculating the amount and concentration of sulfuric acid to generate aerosols. Heated air is assumed to be flowing at the rate of about 0.2 m/s to 0.8 m/s across cross sectional area of 4 ft\(^2\). For our calculation, the average velocity of 0.6 m/s is used. Ninety-eight percent sulfuric acid, diluted to 10% by volume with water, is injected in the injection system at the rate of 1 ml/min, using mini-variable flow peristaltic pump. Aerosol concentration is calculated with only the sulfuric acid concentration and not the concentration of the liquid droplet (water + acid). This is compared to the target value computed in Table 5.5.
<table>
<thead>
<tr>
<th></th>
<th>value</th>
<th>unit</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FLOW CONDITIONS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVERAGE FLOW VELOCITY</td>
<td>0.6</td>
<td>m/s</td>
<td>0.6</td>
<td>m/s</td>
</tr>
<tr>
<td>CROSS SECTIONAL AREA</td>
<td>4</td>
<td>Ft²</td>
<td>0.37</td>
<td>m²</td>
</tr>
<tr>
<td>VOLUMETRIC FLOWRATE OF AIR</td>
<td>0.222</td>
<td>m³/s</td>
<td>0.222</td>
<td>m³/s</td>
</tr>
<tr>
<td><strong>ACID INPUT (liquid)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>98% Sulfuric Acid</td>
<td>0.98</td>
<td>v/v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio of acid to water by volume</td>
<td>0.25</td>
<td>v/v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net ratio of acid to water by volume</td>
<td>0.245</td>
<td>v/v</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACID SOLUTION INJECTION RATE</td>
<td>1</td>
<td>ml/min</td>
<td>1.67×10⁻⁸</td>
<td>m³/sec</td>
</tr>
<tr>
<td>PURE SULFURIC ACID INJECTION RATE</td>
<td>4.08×10⁻⁹</td>
<td>m³/sec</td>
<td>4.08×10⁻⁹</td>
<td>m³/sec</td>
</tr>
<tr>
<td>MASS RATE OF ACID</td>
<td>7.47×10⁻⁶</td>
<td>kg/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ACID INPUT (gas)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mol weight of sulfuric acid</td>
<td>98</td>
<td>g/mol</td>
<td></td>
<td></td>
</tr>
<tr>
<td>molar rate of acid</td>
<td>7.63×10⁻⁸</td>
<td>mol/sec</td>
<td></td>
<td></td>
</tr>
<tr>
<td>temperature of gas</td>
<td>100</td>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration</td>
<td>1.84×10⁻⁸</td>
<td></td>
<td>1.84×10⁻²</td>
<td>PPMV</td>
</tr>
<tr>
<td><strong>STANDARD VALUES</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density of sulfuric acid</td>
<td>1.8305</td>
<td>g/cm³</td>
<td>1830.5</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Density of water</td>
<td>0.998</td>
<td>g/cm³</td>
<td>998</td>
<td>kg/m³</td>
</tr>
</tbody>
</table>

**CONCENTRATION IN µg/m³**

Mass rate of acid = 7.47 ×10⁻⁶ kg/s

Droplet concentration = 3.37×10⁻⁵ kg acid /m³ = 33,669 µg/m³