AN EFFICIENCY PREDICTION THEORY FOR A RESIDENTIAL, CORRUGATED PARALLEL PLATE ELECTROSTATIC PRECIPITATOR

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CHAPTER I

INTRODUCTION

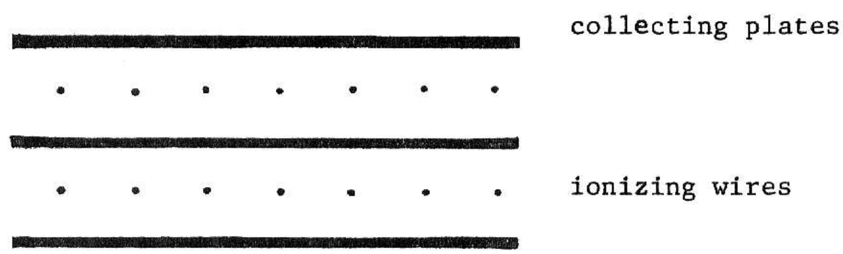
Air pollution is the direct result of growth of our modern technological society and one of its most serious problems today. One of the oldest and most effective means of controlling air contamination by airborne dust is electrical precipitation. Specific operational requirements have led to the development of two types: (1) industrial-type precipitators and (2) residential-type precipitators.

Most published studies and research have been directed toward industrial precipitators. The prolific writings of Gaylord W. Penney and Harry J. White, pioneers in the field, have provided a solid foundation. An extremely limited amount of published research has been devoted to residential parallel-plate precipitators.

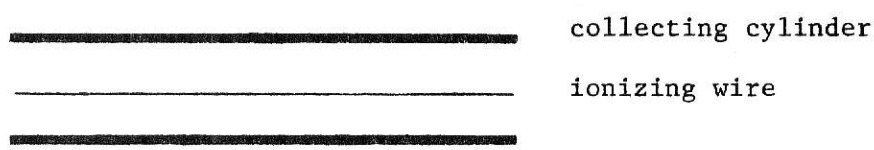
Background Information

Gas cleaning processes may be classified broadly as mechanical and electrical. Mechanical processes include all those which depend fundamentally on the inertia, diffusion mobility, and gravitational attraction of the aerosol being collected.

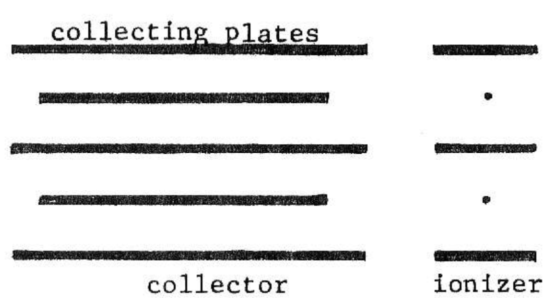
The electrical processes, usually referred to as electrostatic precipitation, differ from mechanical in that the forces of separation acting on the suspended particles are electrical in nature. Electrostatic precipitation can be a highly efficient collection mechanism, capable of efficiencies as high as 99.9% under proper conditions. F. G. Cattrell (1906) converted this phenomenon from a laboratory curiosity to a successful engineering process some sixty-six years ago [1].



(a) single-stage, wire-and-plate



(b) single-stage, wire-in-tube



(c) two-stage, wire-and-plate

Figure 1. Schematic diagrams of single-stage and two-stage precipitator electrode.

Industrial Electrostatic Precipitators. The industrial electrostatic precipitator is a single stage design, with the corona emitted from a fine wire maintained at negative potential. Generally, wire-in-cylinder precipitators are used for small gas flows and wire-and-plate precipitators are used for larger gas flows. Figure 1 illustrates the difference in the types.

White [2] states that the collecting-electrode size for wire-in-cylinder precipitators ranges from 6 in. diameter by 6 ft long to 12 in. diameter by 15 ft long. He also noted that wire-and-plate precipitators have collecting plates 2-8 ft wide and 6-25 ft high.

According to White, most industrial precipitators use steel or steel alloy ionizing wire of about 100-mil diameter and ionizing current of 0.01-1 ma/ft of discharge wire. Operating voltages ranged from 30 to 100 KV.

Residential Electrostatic Precipitators. The residential electrostatic precipitator is two-stage, with positive corona. The ionizing corona is generated by fine smooth wires, approximately 5-10 mils in diameter [2]. This corona is uniform along the wire. Operating voltages range from 5-7 KV. The collection section consists of parallel plates alternating from positive to negative polarities. Collecting-electrode size for wire-and-plate precipitators is typically 24 in. high, 12 in. wide (in flow direction), and 24 in. long.

Although both kinds of precipitators employ the same basic scientific principles, operational requirements for residential air cleaning precipitators are different from those for single stage industrial precipitators.

Penney [3] summarizes the requirements for residential precipitators as follows:

"(1) Ozone generation is a primary limitation, since the ozone generated must be a very small fraction of a part per million.

(2) The dust loading is typically less than one ten-thousandth of the typical loading in dust collection (industrial) applications.

(3) The limited space available makes a design for minimum space imperative.

(4) In the interest of low cost, saving of space, and maintenance by untrained personnel, the voltage should be much lower than that used in industrial dust collecting precipitators."

Ozone may be harmless to humans only when the concentration is on the order of one part per 30 to 40 million. This amount of ozone occurs naturally in the air of many large cities. The original design for air conditioning application limited ozone generation to one part in 200 million.

Penney [3] believes that for a given type of corona discharge the generation of ozone is proportional to corona current. He further suggests that the lower rate of ozone generation is possible by using positive corona from a fine wire.

Penney [3] reported an approximation analysis of the collector cell can be made which shows that the total plate area is independent of plate spacing for a given efficiency and voltage gradient. This analysis shows the total plate area required is directly proportional to the flow rate at any given efficiency. Therefore, the overall volume of the plate section is inversely proportional to the plate spacing. Penney added that plate spacing for residential collectors is usually between 3/16 and 3/8 in. From this analysis one could increase the velocity by increasing the plate length; but, in general, the length of a single plate does not exceed 12 in.

Objectives

The first objective of this study was to observe and determine the flow characteristics through the corrugated parallel plates of the electrostatic precipitator.

The second objective was to derive a theoretical stain efficiency prediction relation fitting previously obtained experimental data [4].

CHAPTER II

ANALYSIS OF PRECIPITATION

An electrical precipitator is defined as an apparatus that utilizes electric forces to separate suspended particles from gases. In practice, electrical precipitators are of various physical configurations, but all are designed from the same principles.

Corona Generation

Corona, as applied to electrostatic precipitator, is a gas discharge phenomenon associated with the ionization of gas molecules by electron collision in regions of high electric field strength. The process of corona generation requires a nonuniform electric field, which is obtained by use of a small diameter wire as one electrode and a plate or cylinder as the other electrode.

The two types of corona used in electrostatic precipitation are classified as negative and positive, depending on the polarity of the corona wire. Positive corona is used in most residential electrostatic air cleaners. The advantage of positive corona is that ozone generation is nil.

In the corona process, there must be a source of electrons to initiate and maintain the process. The electrons to initiate corona are supplied by naturally occurring ionizing radiation. Since they are in a region of high electric field, they accelerate to high velocities and possess enough energy so that on impact with gas molecules in the region, they release orbital electrons from gas molecules.

Particle Charging

There are two mechanisms responsible for the charging of particles in an electrostatic precipitator. These mechanisms are termed field charging and diffusion charging.

Diffusion charging is predominant for small particles with diameters less than about 0.4 micron. The diffusion charging process depends on the thermal energy of naturally-occurring ions, not on an electric field, and is the result of ionic collision with particles brought about by random Brownian motion of ions in the gas.

Field charging is more effective for large particles with diameters greater than about 1.0 micron. In this type of charging, the particles are charged by the attachment of ions in an electric field. Both diffusion and field charging are important for particles in the intermediate size range of 0.4 to 1.0 micron.

Electrical charging may occur naturally during the formation of a particle. The magnitude of the charge will be low, unless the particle was the recent product of combustion or atomization. However, high-voltage direct-current corona can charge particles to much higher levels. The ionizing field is usually established between an active electrode (a fine wire in this case), maintained at high voltage, and a plate or cylindrical electrode at ground potential. Under these conditions an ionizing corona is generated in the strong electric field region near the wire surface. Considerable numbers of positive ions are formed in this active "glow" zone. In the charging process, particles passing through the ionizing field are subjected to bombardment by these ions and become highly charged. These charged particles then migrate toward the collecting electrode.

Particle Collection

Collection of the charged particles is effected by subjecting them to a high-voltage direct-current field maintained between electrodes. The collecting field may be either a continuation of the corona, as in a single-stage precipitator, or it may be purely non-ionizing electrostatic field between nondischarging electrodes as in a two-stage arrangement.

In a two-stage precipitator the corona, emitted from the fine wire, is maintained at a high positive potential. Dust particles enter the ionizing section, become highly charged and pass into the plate section where they are collected.

Adhesive Forces. In electrostatic precipitation, electrostatic forces drive the particles to the collecting surface. But in many cases, after the particle touches the surface, the force reverses and tends to pull the dust off the plates. Adhesion is therefore of primary importance in holding the deposited dust on the collecting surface.

It has been known that adhesive forces are due to the attraction between areas of opposite polarity distributed over the surface of the particle. Penney [4] shows it is possible to form highly adhering deposits of dust without the aid of an applied electric field. He reported that the forces in these deposits do not seem to depend on any alignment of particles, in which each acts as an individual electric dipole.

In order to bring the former dipole hypothesis of adhesion into agreement with experiment, Penney proposed a modified hypothesis which assumes that the surface of particles as small as 10 microns may be covered by numerous positive and negative areas. The adhesive forces are the result of attraction between small areas of opposite polarity.

Penney concluded that higher humidity appears to increase the adhesive properties of particles. However, this may be over-balanced by a looser packing of the particles brought about by the lower resistivity.

Particle Trajectories. From the observations of Seman and Penney [5] on particle trajectories, it was concluded that the mechanical impact of large particles is a serious disturbing factor in precipitation. The magnitude of the effect and how it varies with the particle size was to be the subject of their further studies. However, in the present theory of electrostatic precipitation, it is assumed that the particles are collected when they touch the collecting surface.

Penney's photographic records [6,7] of the path of 100-micron particles show that typically, with a clean surface, particles bounce off the surface without losing their electric charge. When particles strike a layer of previously deposited particles, the larger ones not only bounce off but knock loose some of those previously deposited.

Dust Resistivity. Penney [8] reported that high resistivity dusts may result in excessive voltage gradients across the layer of collected dust and cause reverse-ionization. He added that reverse-ionization reduces the efficiency of precipitation and causes excessive ozone generation and wire vibration. Control of humidity and use of adhesive is an effective means of eliminating this problem.

Collection Efficiency

The equation for the collection efficiency of an electrostatic precipitator was discovered experimentally by Evald Anderson [9] in 1919. In 1922 Deutsch developed from theory a similar equation for the efficiency of such precipitators. White [2] derived an identical expression based on the probability of collection for a single particle. This derivation led to an efficiency equation of the form

$$\eta = 1 - \exp[(-A/V_g)(w)] \quad (1)$$

where:

A = collection surface area

V_g = gas flow rate

w = particle velocity.

Penney [10] in 1969 indicated some problems in the application of the Deutsch equation. He enumerated the assumptions that had been made to derive that equation and indicated that they would never occur with industrial dust. He pointed out that in the two-stage type precipitator which is used for cleaning ventilating air, the low level of turbulence tends to give an efficiency increasing more rapidly with plate length than would be predicted by the Deutsch equation.

CHAPTER III

FLUID FLOW STUDY

In order to determine the flow pattern through the parallel plates of the precipitator, it was necessary, first, to calculate the Reynolds Number. From Knudsen [11]

$$N_{Re} = \frac{2bU\rho}{\mu} \tag{2}$$

where:

b = spacing between plates

U = average velocity

ρ = particle density

μ = gas viscosity.

The maximum Reynolds Number calculated, based on the maximum CFM through the test duct, was 2355, using the gross entrance area. Knudsen [11] reports experimental studies always found laminar flow at Re < 2,000. Turbulent flow might not occur until Re > 21,200 under ideal conditions [11], necessitating a smoke study to ascertain the exact situation for this case.

Equipment and Procedure

A wind tunnel, designed commercially for aerodynamic smoke studies, was used to determine the flow pattern through the electrostatic collector's corrugated parallel plates. The tunnel overall was 33 in. high, 19 in. wide and 71 in. long, consisting of following sections, shown in Fig. 2 and Fig. 3.

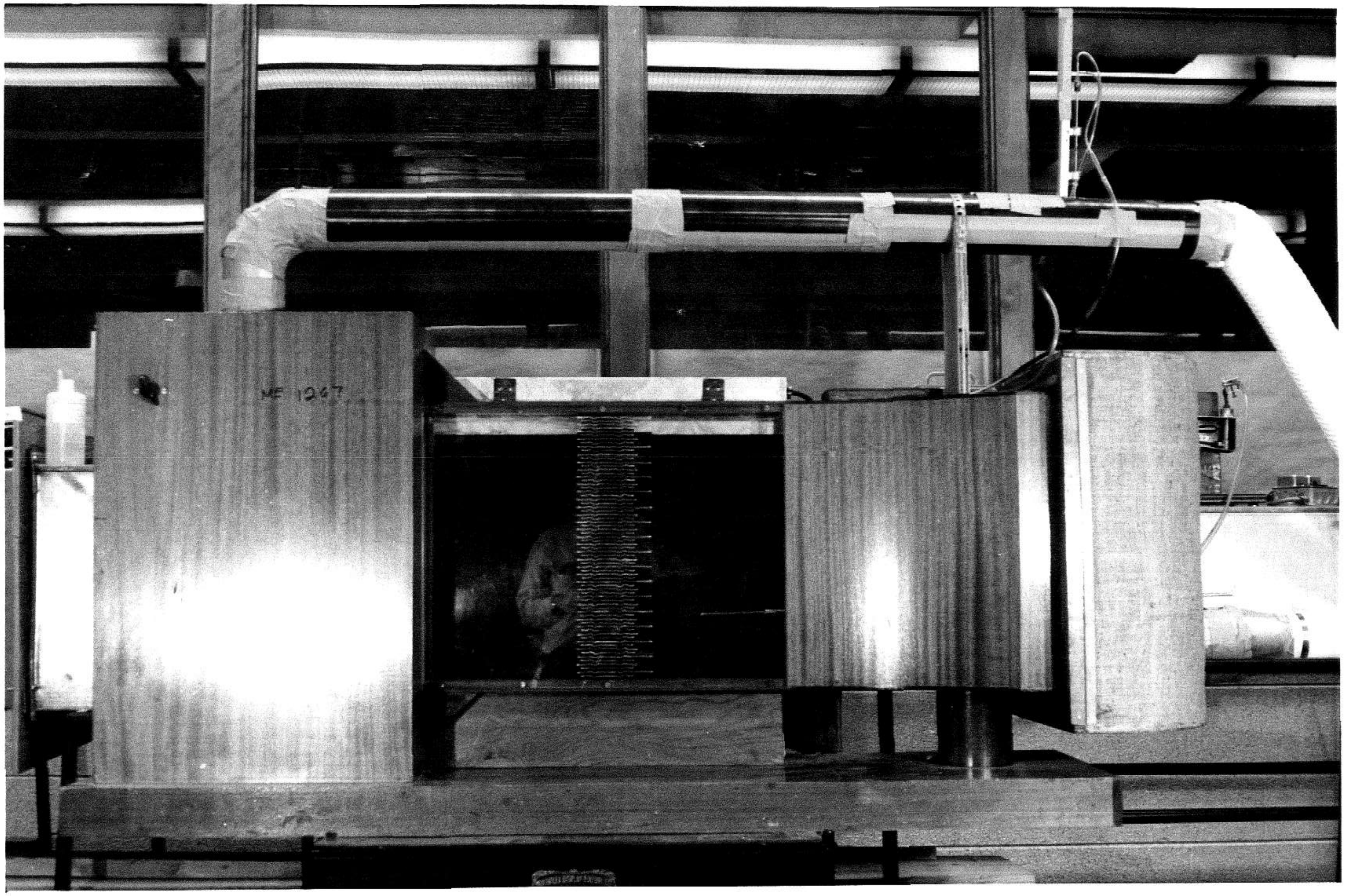


Figure 2. Photograph of the wind tunnel.

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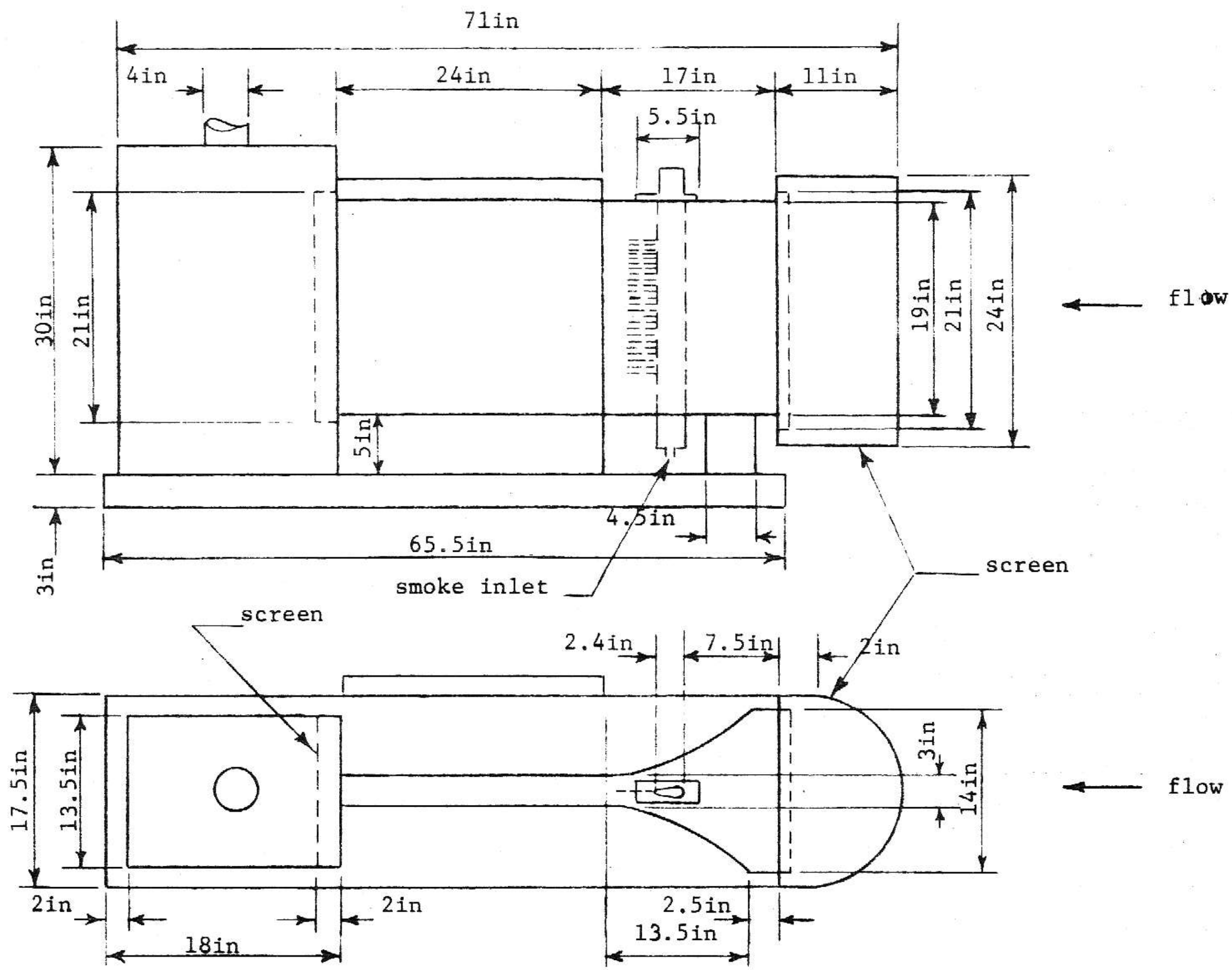


Figure 3. Schematic drawing of the wind tunnel

(1) Inlet section. This section consisted of a semi-circular screen acting as a flow straightener to insure laminar flow. A vertical, elliptical smoke inlet manifold with 37 horizontal outlets was located 7.5 in. in from the screen. Smoke was injected into the manifold from the bottom.

(2) Test section. Two 19 x 24 in. Plexiglas plates permitted observation of the flow patterns from either side.

(3) Outlet section. A screen was located between the test section and outlet section to eliminate turbulence from the exhaust fan.

Plates were carefully cut and glued in the test section. A special smoke was introduced to the test section through 34 horizontal pipes of the input section. A blower was used to draw air through the section. With variation in damper opening, the flow rate was adjusted.

Since smoke was not sufficiently concentrated, it was not possible to discern any flow pattern. The chemical composition of the smoke was such that it would attach to the metal of the input pipes and plug up their openings immediately.

A long, thin glass tube was used to overcome the difficulties encountered in the first method. Air blown over the chemical to produce smoke helped the smoke flow through the tube and into the air stream. The concentration of smoke was high, since only one tube was used, and it did not plug the glass tube as rapidly. Since there was only one stream of smoke, it was easily controlled and maintained at a certain location.

Results

From the smoke study, Fig. 4, it was observed that the smoke stream would stay intact through the plates. The smoke did not parallel the corrugations of the plate completely because of the change in velocity

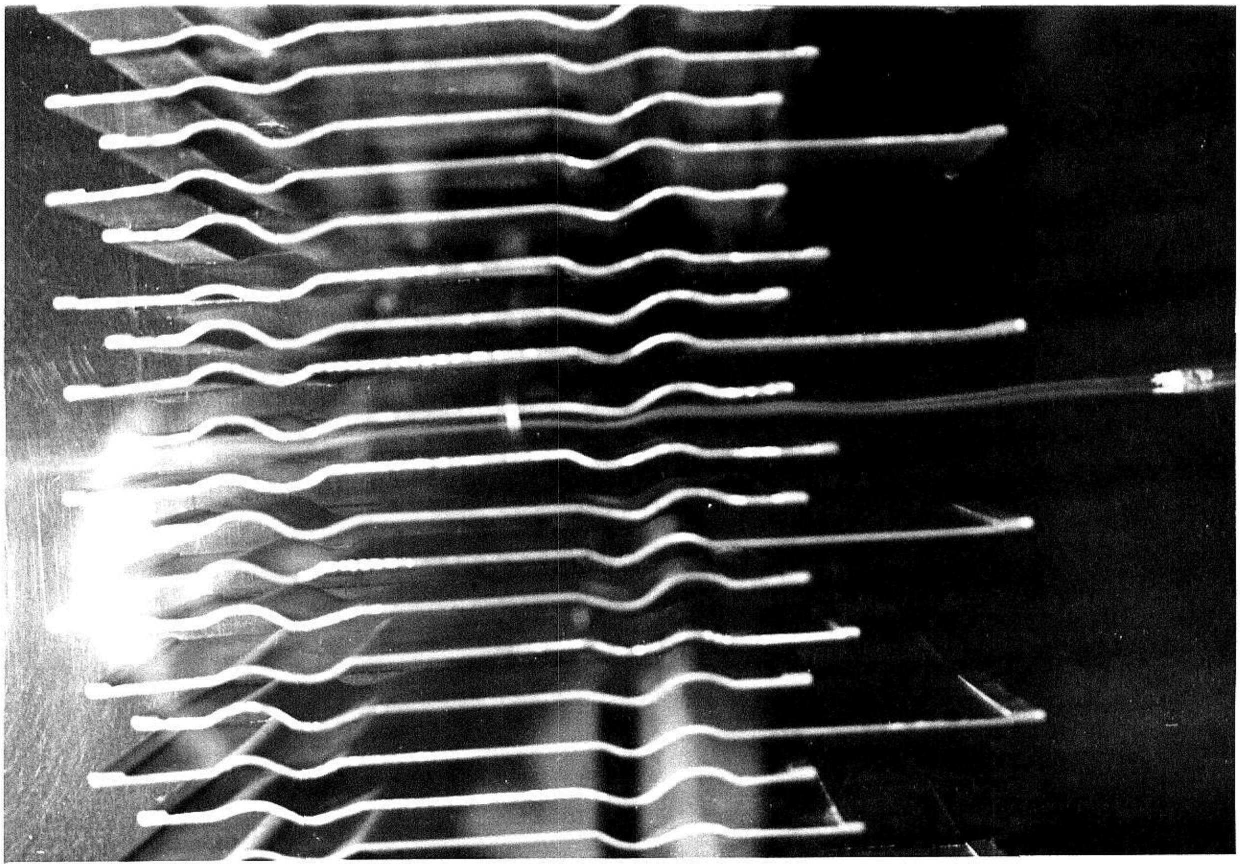


Figure 4. Smoke pattern through parallel plates of Metal-Fab cell.

profile. In a straight section, the maximum velocity occurred in the center. When the flow reached the corrugation, the maximum velocity tended to move from the center causing the velocity profile to shift. A lower velocity existed under the curvature of plates. Fig. 5 illustrates the velocity profile variation between two parallel plates.

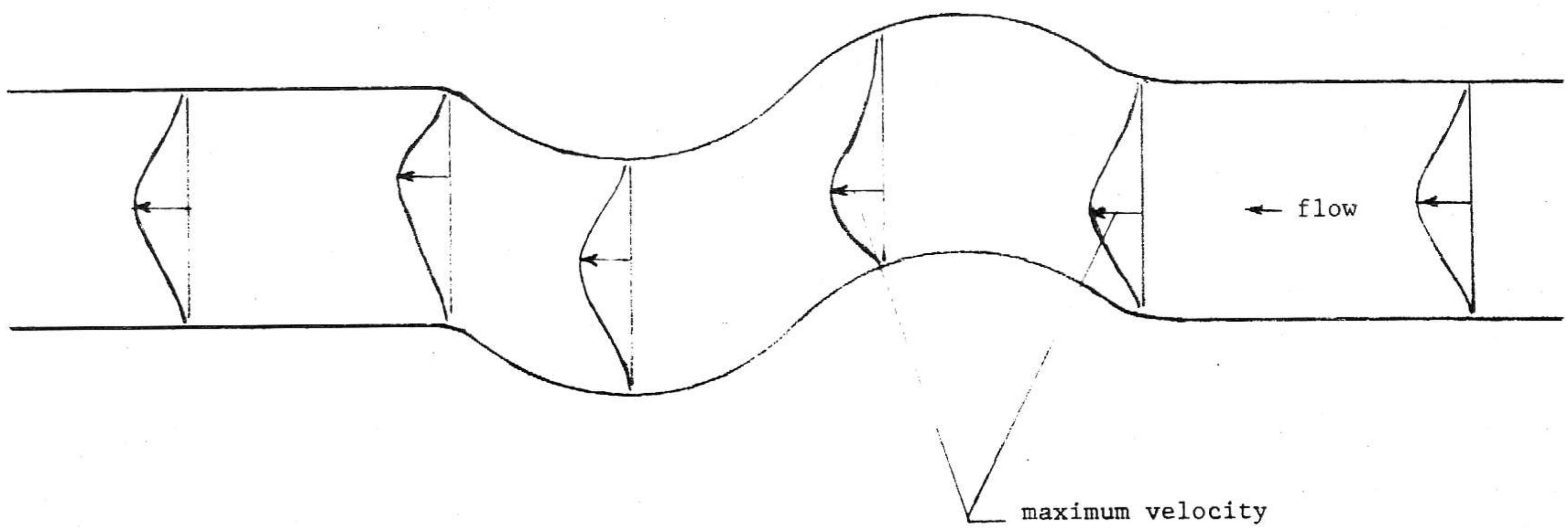


Figure 5. Velocity profile through corrugated parallel plates.

CHAPTER IV

COLLECTION EFFICIENCY ANALYSIS

Nearly fifty years ago, Deutsch [2] developed the following equation for the efficiency of an electrostatic precipitator:

$$\text{Efficiency, } E_t = 100(1 - e^{-Av/Q}), \% \quad (3)$$

where:

A = area of collecting surface

v = the electrically induced drift velocity toward the collecting surface

Q = volume rate of air flow through the precipitator.

The derivation of this equation requires four assumptions:

(1) A particle is collected once it touches the collecting surface;

(2) All particles are of the same size and no agglomeration occurs;

(3) Each particle behaves independently of the other particles;

(4) The particles are uniformly distributed over any given cross-section of the precipitator.

These assumptions on which the Deutsch equation is based rarely occur with industrial or residential dusts.

In order to better understand the electric field pattern of the ionizing wire and parallel plates, the equal-potential lines were found by the use of Teledeltos paper. Figures 6 , 7 and 8 show the arrangements of these lines. From these figures, it is obvious that most of the ionization is done around and close to the wire. There, the potential gradient is the steepest and the field strength decreases less rapidly as it gets farther from the wire.

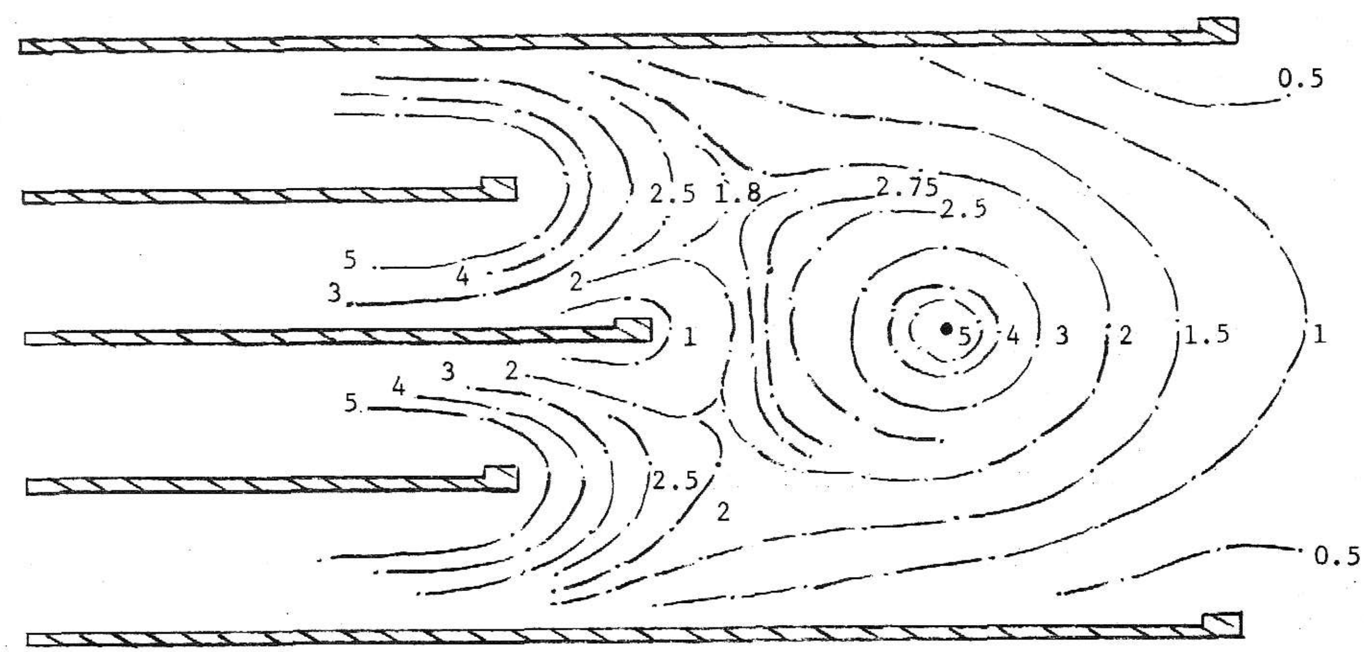


Figure 6. Equal potential lines in a flat parallel plate cell.

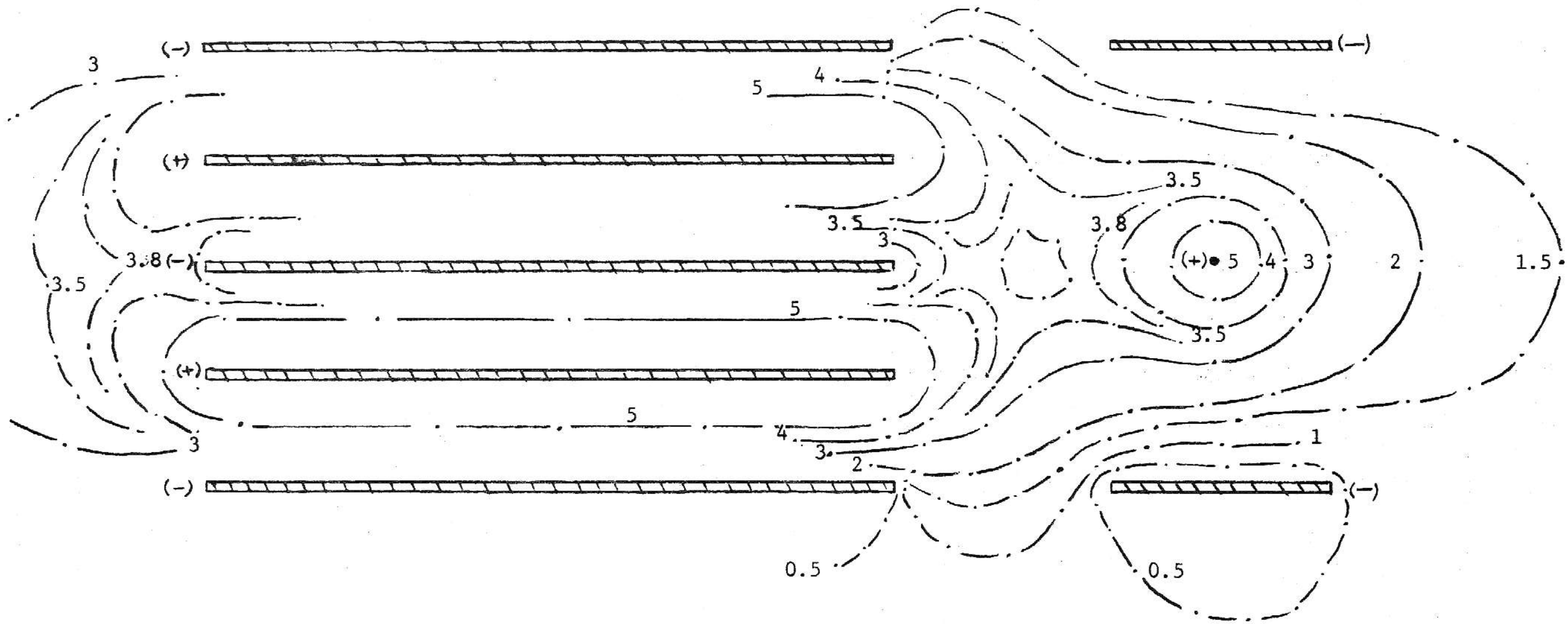


Figure 7. Equal potential lines in a flat parallel plate cell (two stage).

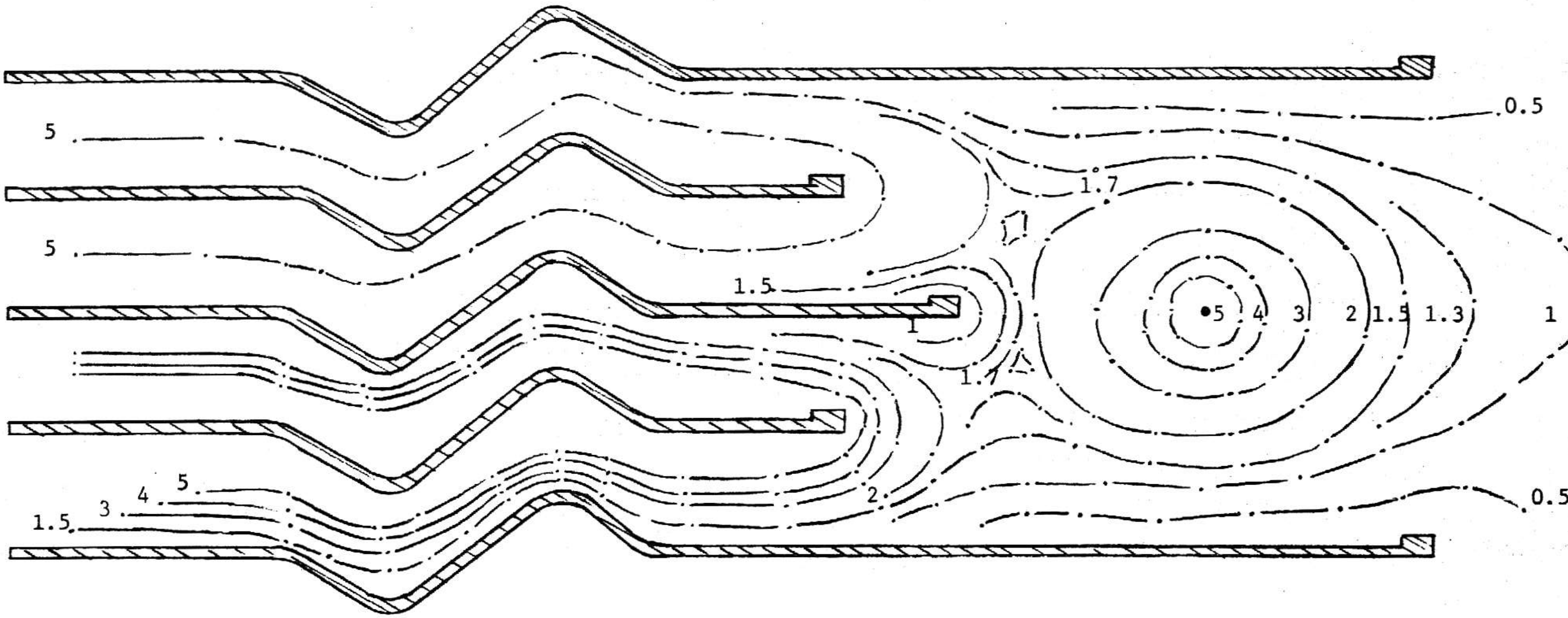


Figure 8. Equal potential lines in a corrugated parallel plate cell.

Particle Kinetics

The motion of a charged particle under the influence of an electric field is governed by Newton's Law of Classical Mechanics. The four principal forces acting on a particle in a precipitator are [9, p. 97]:

(1) Electrical Force

$$F_e = q\ E \tag{4}$$

(2) Viscous Force

$$F_\eta = u/Z,\ Z = C/3\pi\ \mu_f\ D_p\ (cm) \tag{5}$$

(3) Inertia Force

$$F_i = mdu/dt \tag{6}$$

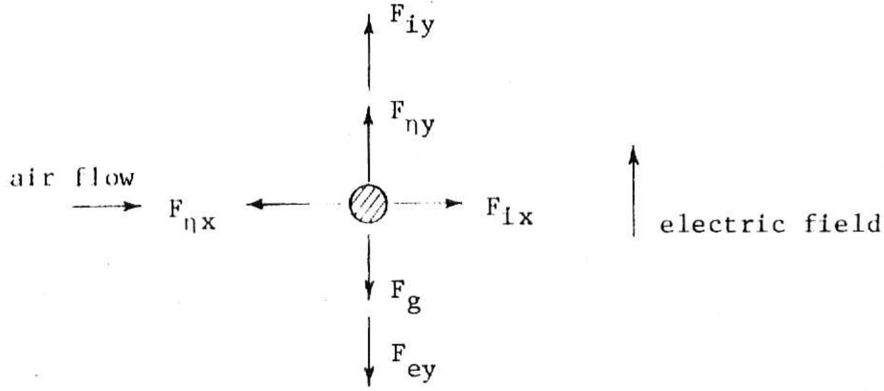
(4) Gravitational Force

$$F_g = mg \tag{7}$$

where:

E = electric field (gradient)	u = particle velocity
q = charge on particle	m = particle mass
μ_f = fluid viscosity	g = acceleration of gravity
D_p = particle diameter	C = Cunningham coefficient
	v = fluid velocity

A free-body diagram of the above forces acting on a negatively charged particle is shown below.



Summing the forces in x and y direction gives:

$$\sum F_x = F_{ix} - F_{\ x} = 0 \qquad (8)$$

since $u_x = v_x$ = constant, thus $F_{ix} = 0$, $F_{\eta x} = 0$

$$\sum F_y = F_{iy} + F_{\eta y} - F_g - F_{ey} = 0 \qquad (9)$$

Assuming laminar flow, the vertical component of air velocity, v_y, equals zero. Substituting values for the forces we get:

$$m \frac{du_y}{dt} = F_g + F_{ey} - F_{\eta y} \qquad (10)$$

Since gravitational force is very small by comparison to the electrical force, it is assumed to be negligible [9, p. 99]. The form is simplified to:

$$m \frac{du_y}{dt} = F_{ey} - F_{\eta y} \qquad (11)$$

Electrical force, $F_{ey} = q(4.8 \times 10^{-8}$ esu/e$)(3.3 \times 10^{-3}$ esu/v/cm$)\ E_c$

$= 1.6 \times 10^{-12}\ q\ E_c$

where:

q = particle charge, electron charges

E_c = collector field, volts/cm.

From equation (11), set $du_y/dt = 0$ as terminal velocity is quickly attained [9],

then $F_{ey} = F_{\eta y}$ (12)

Substituting values for F_{ey} and $F_{\eta y}$ into equation (12) gives:

$$1.6 \times 10^{-12}\ q\ E_c = \frac{u_y\ (3\pi\ \mu_f\ D_p\ (\text{cm}))}{C} \qquad (13)$$

Simplifying equation (13) to find:

$$u_y = \frac{1.6 \times 10^{-12}\ q\ E_c\ C}{3\pi\ \mu_f\ D_p\ (\text{cm})} \qquad (14)$$

From empirical data [11]:

$$q = E_i^{0.59} \, D_p(\mu)^{0.162 \ln(4.31 E_i)} \tag{15}$$

Electrical Field of Ionizing Section

In a wire-in-tube precipitator, Gottschlich [13] suggested the use of:

$$E_i = \left(\frac{c^2}{r^2} - \frac{i}{2\pi K_0 K}\right), \quad c = \frac{V}{\ln\frac{R_1}{R_2}} \tag{16}$$

where:

c = constant of integration, volts

r = radial distance measured from the centerline of the discharge electrode, meters

i = electrical current per unit length of the discharge electrode, amp/m

K_0 = dielectric constant of a vacuum, 8.85434×10^{-12} $Coul^2/Joul\text{-}m$

K = ion mobility, $m^2/v\text{-}sec$

V = voltage difference between electrodes, volts

R_1 = discharge electrode radius, meters

R_2 = collecting electrode radius, meters

Equation (16) can be simplified for certain special cases. For larger values of i and r, a convenient approximation of equation (16) is:

$$E_i = \sqrt{\frac{i}{2\pi K_0 K}} \tag{17}$$

Gottschlich and Troost [13,14] suggested that the electrical field in a wire-and-plate precipitator is:

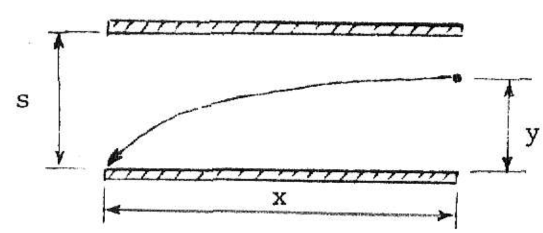
$$E_i = \sqrt{\frac{2id}{\pi\ K_0\ Kh}} \tag{18}$$

where:

d = spacing between the discharge and plate electrodes, meter

h = average spacing between discharge electrode, meter

The efficiency is determined as the ratio of the distance, collecting plate to most distant particle which could be collected, to the spacing between collecting electrodes. If y = distance from collecting plate to most distant particle which could be collected and s = distance between plates as shown below,



then:

$$\text{efficiency} = \frac{y}{s} \tag{19}$$

Maximum time to collect given particle size, $t = \frac{y}{u_y}$ (20)

The horizontal distance available to collect, $x = Vt$ (21)

where:

u_y = particle velocity in vertical direction

x = length of plate (maximum horizontal distance required to stop)

V = air velocity

Substituting equations (20) and (21) into equation (19) gives:

$$\text{efficiency} = \frac{x u_y}{V\ s} \tag{22}$$

Substituting the u_y value from equation (14) into equation (22) gives:

$$\text{efficiency} = \frac{x\left(\frac{1.6 \times 10^{-12}\ q\ E_c\ C}{3\pi\ \mu_f\ D_p\ (\text{cm})}\right)}{V\ s} \tag{23}$$

Since x = 10.16 cm and s = 0.635 cm, equation (23) simplifies to:

$$\text{efficiency} = \frac{(1.446 \times 10^{-4})\ C\ E_c\ q}{V\ D_p}, \quad D_p \text{ is in microns} \tag{24}$$

Replacing q by its value from equation (15) yields the efficiency equation of:

$$\text{efficiency} = \frac{(1.446 \times 10^{-4})\ C\ E_c[E_i^{0.59}\ D_p^{0.162}\ \ln(4.31\ E_i)]}{V\ D_p} \tag{25}$$

where:

C = Cunningham coefficient

E_c = electric field of collecting section, volts/cm

E_i = electric field of ionizing section, volts/cm

D_p = particle diameter, micron

V = air velocity, cm/sec

CHAPTER V

EFFICIENCY TEST FACILITIES, APPARATUS, AND PROCEDURE

This research project was carried out in the Fine Particle-Air Pollution Laboratory, Institute for Environmental Research and the Mechanical Engineering Department, Kansas State University.

Precipitator Cell

The cells, made by Metal-Fab, Inc. of Wichita, Kansas, were of three types. Type YA32 contained 8 wires of 6-mil diameter. It was 8 in. high, 5 in. wide (in flow direction), and 14 in. long. Two configurations of type YA34 were tested, one containing ten 6-mil wires and the other ten 7-mil wires. It was 10.5 in. high, 5 in. wide (in flow direction), and 14 in. long. Type YA36 contained 12 6-mil wires. It was 12 in. high, 5 in. wide (in flow direction), and 14 in. long.

The cells were considered to be of the two-stage type, in which the ionizing section precedes the collecting section. Figure 9 is a schematic drawing of the Metal-Fab cell. Each positive ionizing wire was between two parallel plates of negative polarity. Within those two parallel plates there were three other parallel plates, one negative and the other two positive. Figures 10 and 11 show photographs of Metal-Fab cell.

A screen located ahead of the ionizing section acted as a pre-filter. The screen, negative plates, and the case were grounded while the positive plates and wires were connected and insulated from ground.

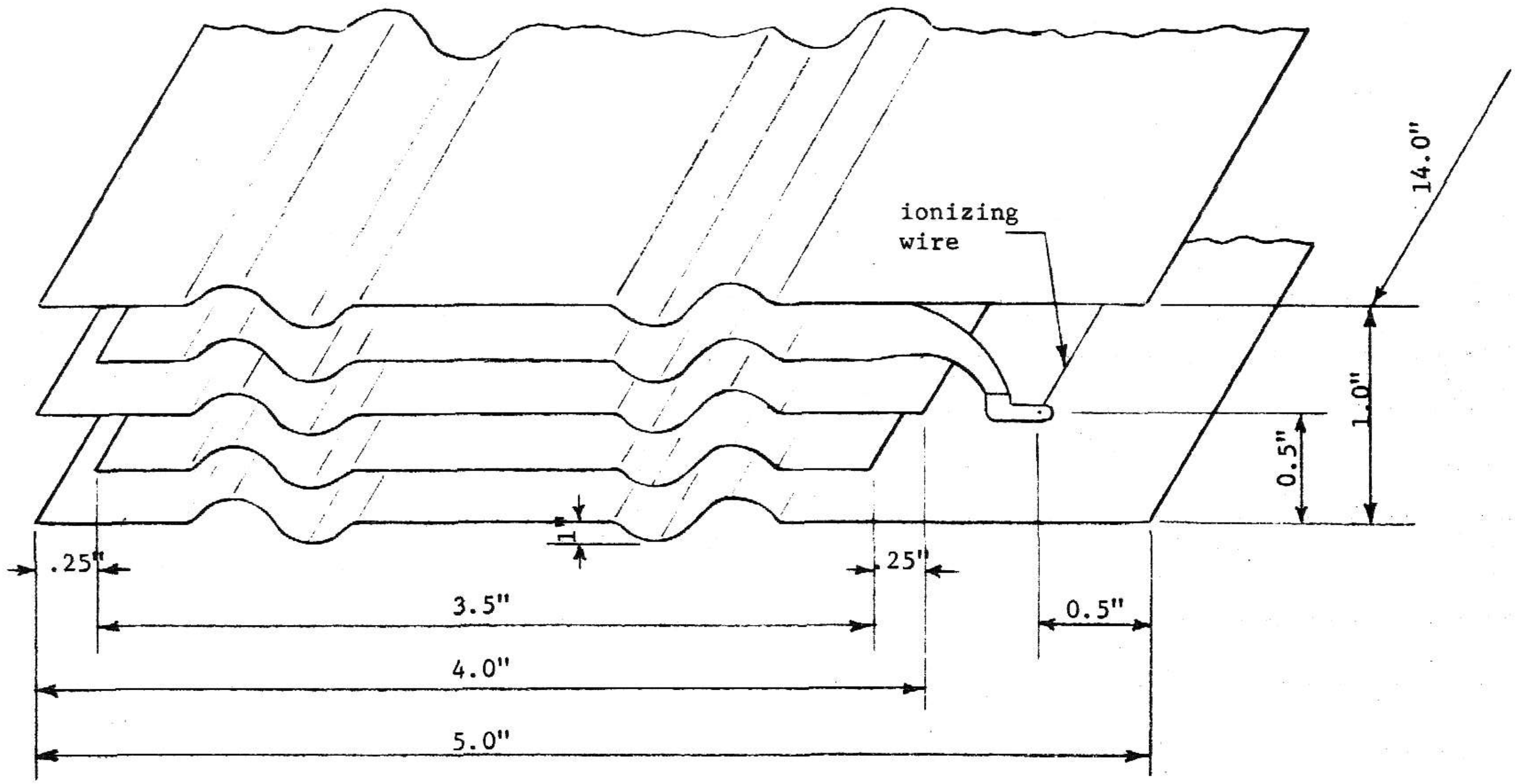


Figure 9. Schematic drawing of Metal-Fab plate arrangement.

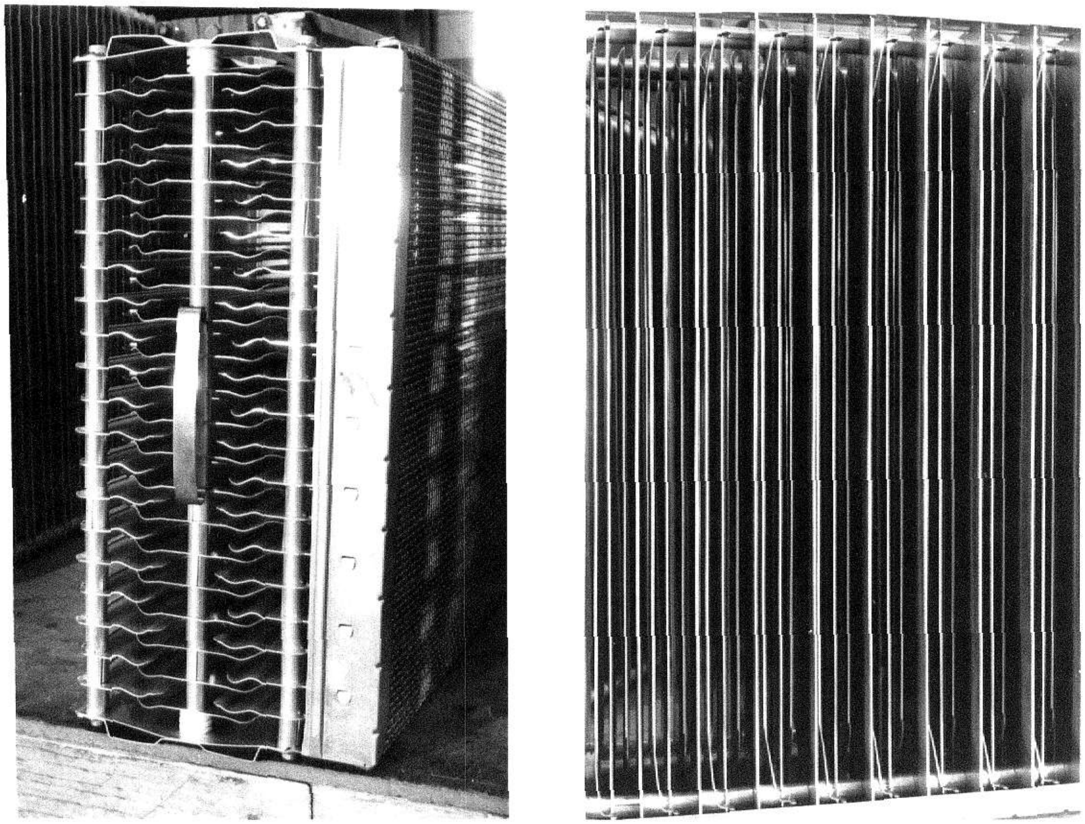


Figure 10. Photographs of the side view and front view of Metal-Fab cell.

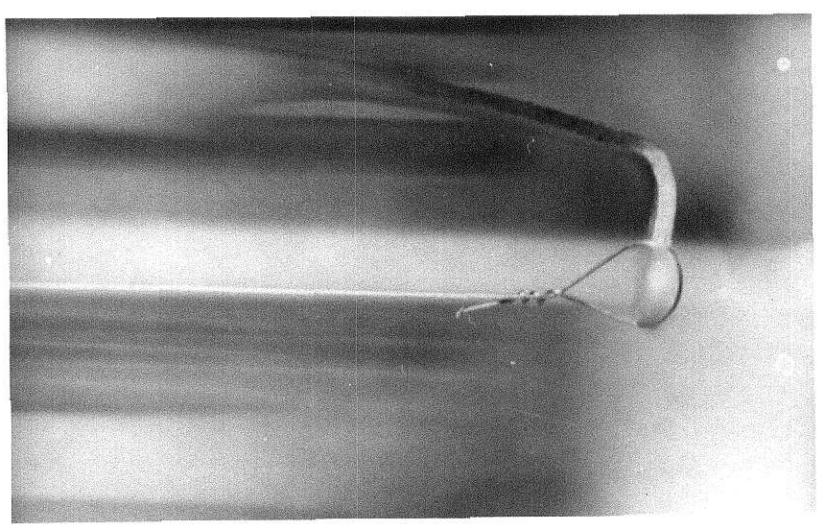


Figure 11. Photograph of the ionizing wire of Metal-Fab cell.

Test Duct

The experimental data was reported by Annis [4]. The sampling system was according to Whitby [15]. This method and equipment essentially meets ASHRAE Standard 52-68. Figures 12 and 13 illustrate the size and configuration of the test duct. Figure 14 is a photograph of the light-scattering photometer and Fig. 15 is a schematic drawing of the same unit.

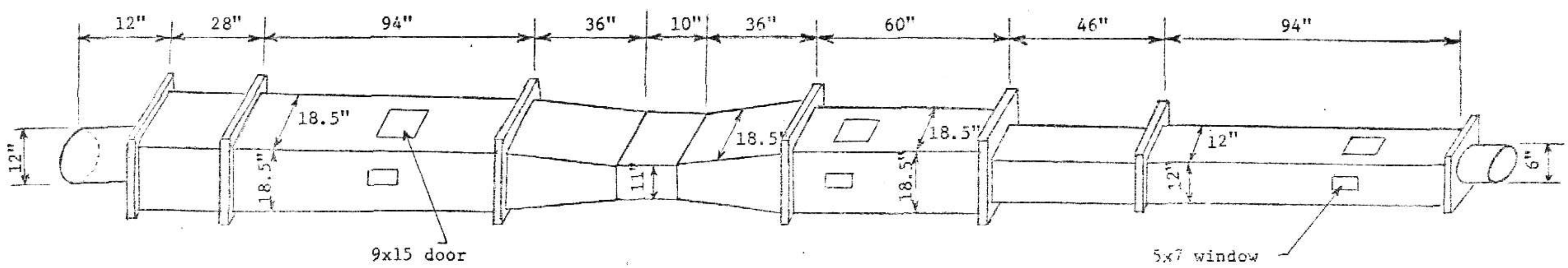


Figure 12. Schematic drawing of the test duct.

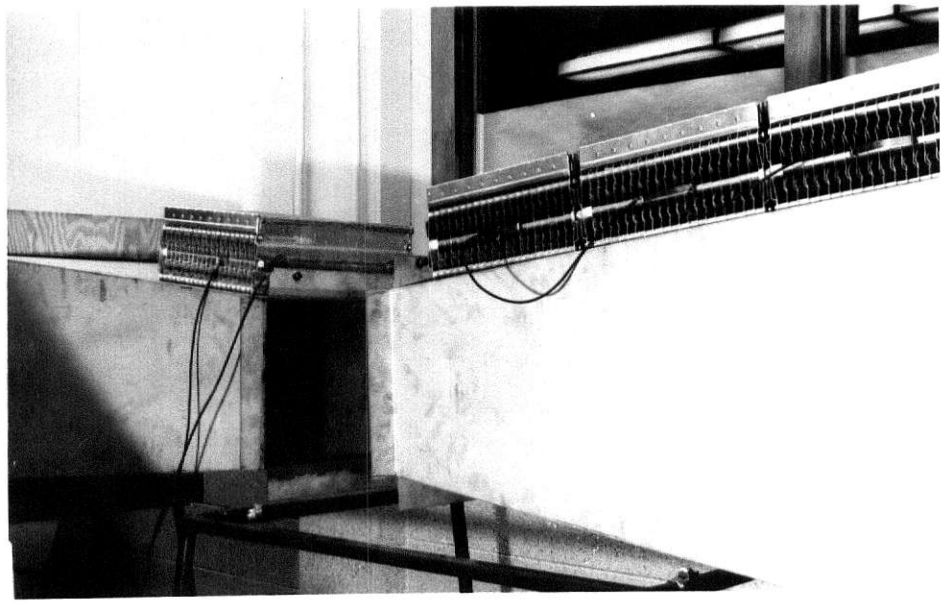


Figure 13. Photograph of the test duct.

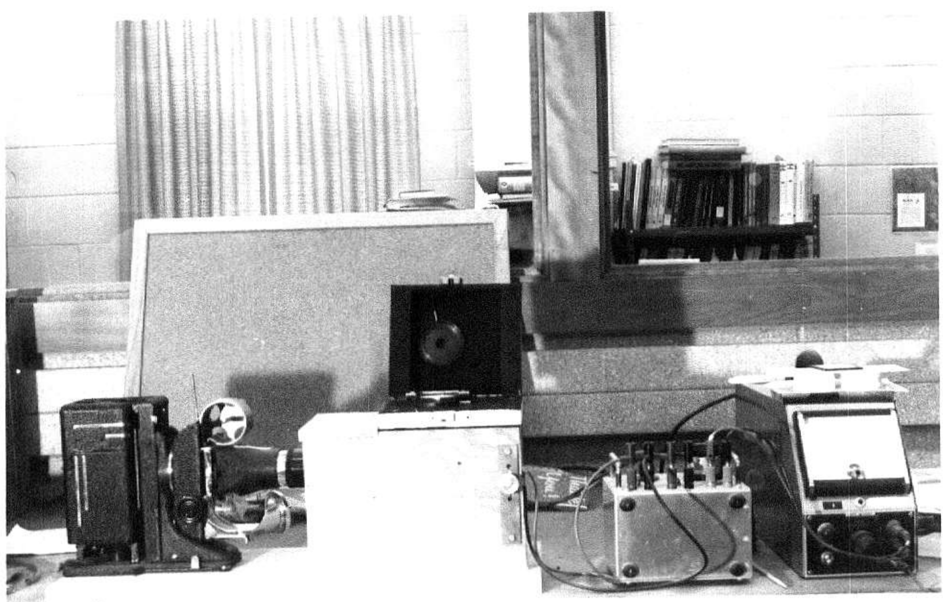


Figure 14. Photograph of the light-scattering photometer.

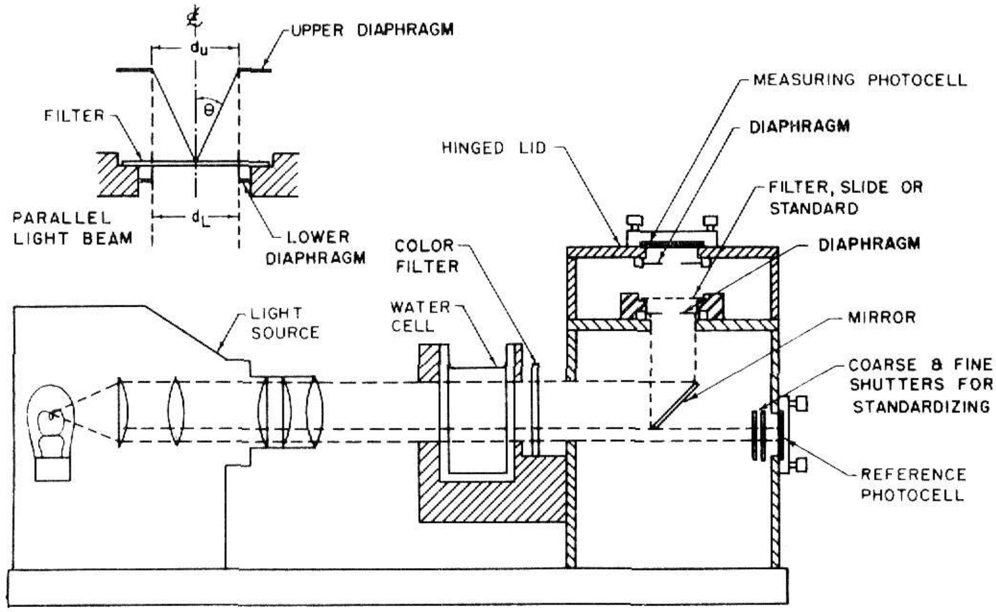


Figure 15. Schematic drawing of the photometer.

CHAPTER VI

RESULTS AND DISCUSSION

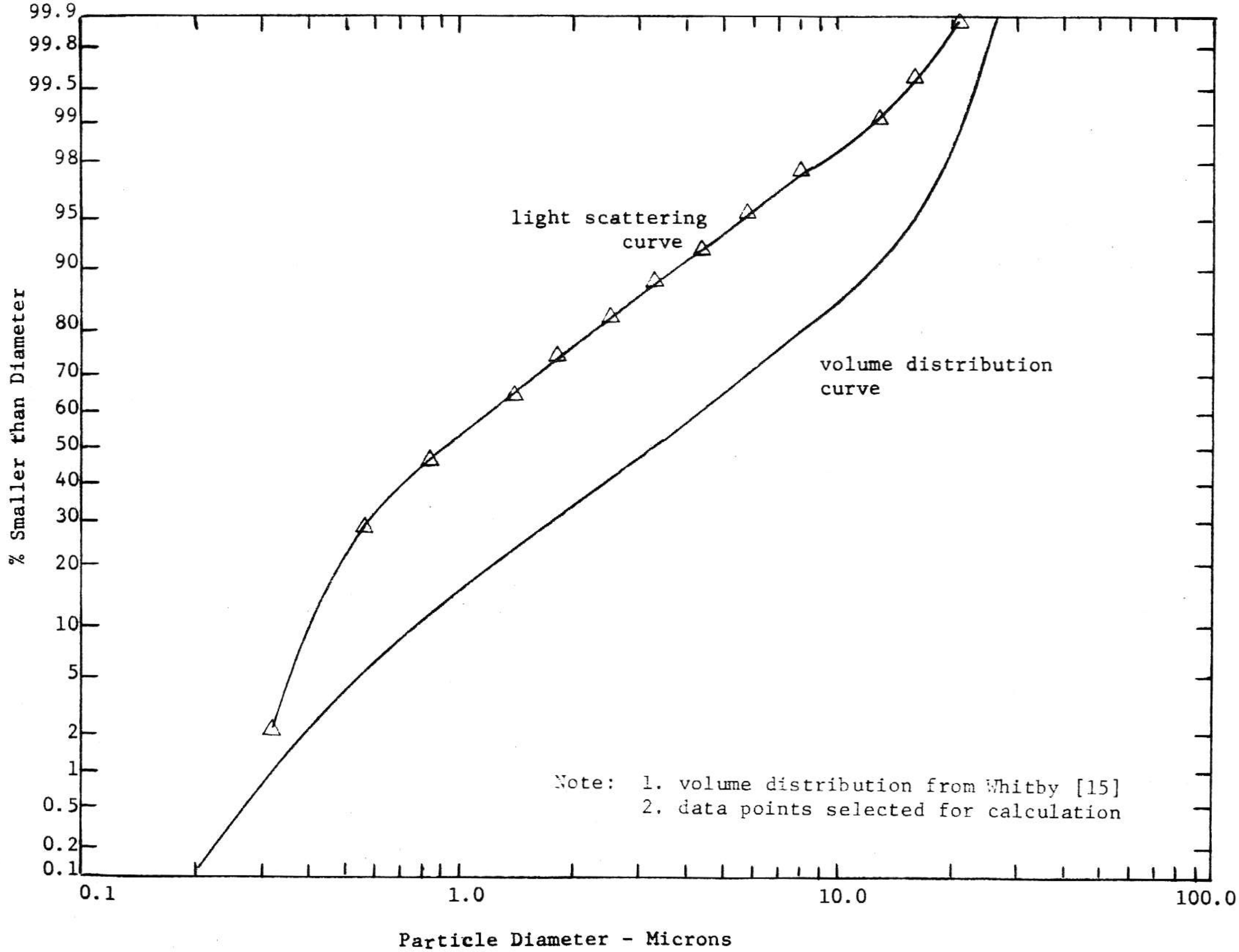
The experimental efficiencies reported by Annis [4] were used for comparison with theoretical calculated efficiency values. Summary of the efficiencies reported by Annis are tabulated in Table 10.

The efficiency equation (25) was used to calculate the stain efficiency of the precipitator. Whitby's [15] volume-weighted size distribution for average atmospheric dust was used along with light-scattering coefficient values from Whitby [16] to determine the stain distribution. The volume distribution and stain distribution are shown in Fig. 16.
The stain-weighted, size distribution was found to be:

Percentile mid points	D_p - μ
95	5.50
85	2.75
75	1.80
65	1.40
55	1.06
45	0.80
35	0.65
25	0.53
15	0.45
5	0.36

To determine the air velocity through the precipitator, several areas were considered to be effective. These areas are:

Figure 16. Volume and light-scattering distribution of atmospheric aerosol.



A_1 - based on the front area, not considering plate thickness or any dead areas.

A_2 - based on the front area less plate thickness.

A_3 - based on the front area less thickness of the folding edge.

A_4 - based on the front area less dead area on each side of plates. (From observation of a dirty cell it was concluded there were areas on each end of the plates that were not collecting dust. Therefore, the particle velocity should be calculated realizing these dead areas.)

A_5 - based on the front area less plate thickness less dead area on each side of plates.

Table 9 in Appendix B shows the velocity calculations for these areas.

Calculated efficiencies based on formula (25) are summarized in Table 1. The same comparison between cfm and efficiencies is shown graphically in Fig. 17. Comparison of calculated efficiencies by the old method and newly derived formula along with experimental values are shown in Table 2.

TABLE 1

SUMMARY OF STAIN EFFICIENCY COMPARISONS

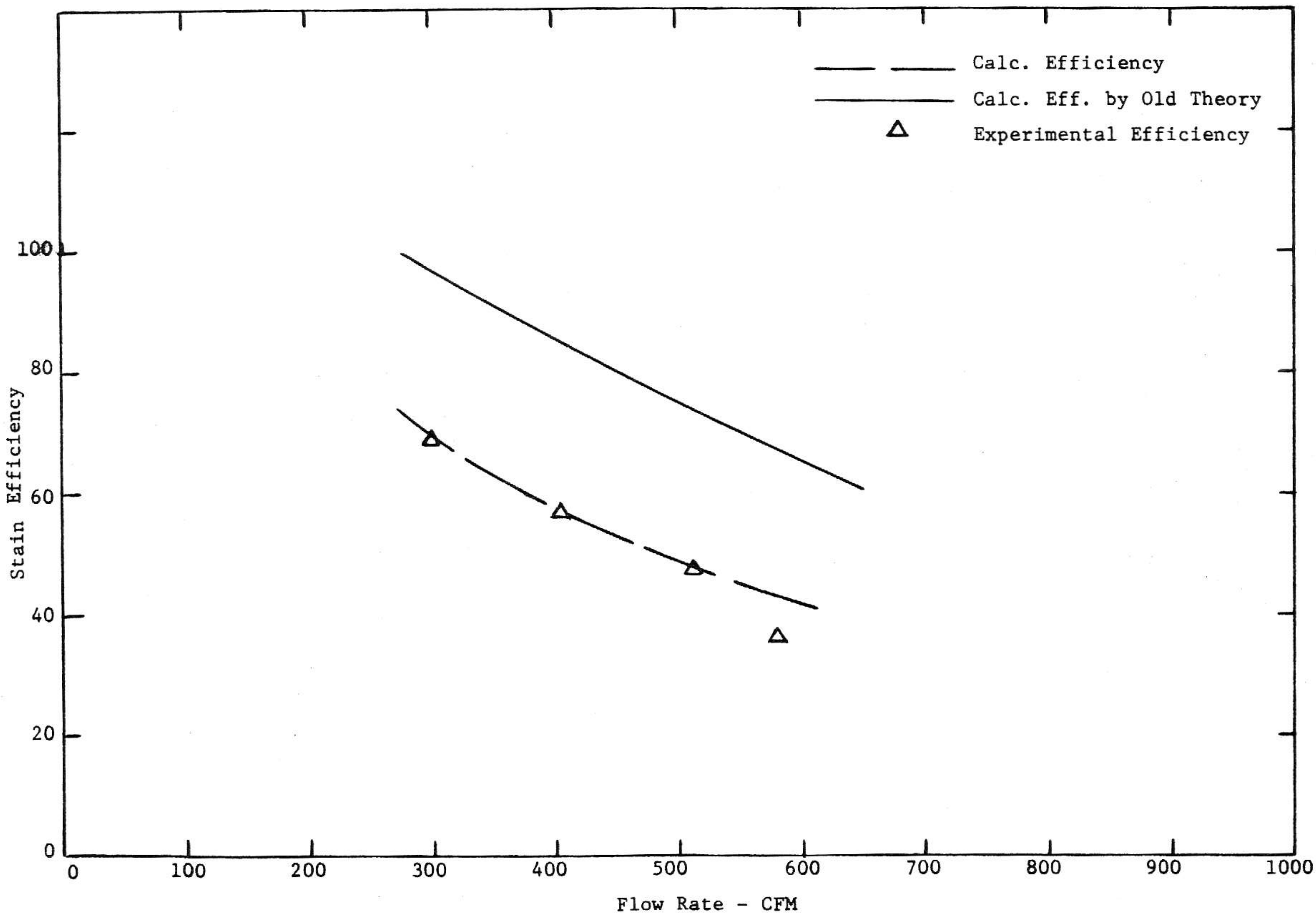
Case No.	No. of Wires	Wire Size	Current mili-amp	Voltage volts	Flow CFM	E_i v/cm	E_c v/cm	Calc. Eff. %	Exp. Eff. %	No. of Runs	$s/\overline{Eff.}$
I	10	7 mil	0.40	6100	300	1763	9606	70.02	69.40	2	0.006
II	10	7 mil	0.40	6095	405	1763	9598	57.13	57.50	4	0.005
III	10	7 mil	0.40	6118	512	1763	9635	47.69	47.90	4	0.003
IV	10	7 mil	0.40	6108	580	1763	9619	43.20	38.10	4	0.089
V	48	6 mil	2.30	6068	300	1932	9556	75.26	75.60	3	0.003
VI	40	6 mil	2.23	6095	300	2083	9598	77.62	69.65	6	0.077
VII	32	6 mil	1.95	6218	300	2179	9792	80.49	79.15	4	0.012
VIII	40	7 mil	1.86	6250	300	1903	9843	76.26	77.97	3	0.016
IX	24	6 mil	1.63	6263	300	2300	9863	82.16	83.27	3	0.009

TABLE 2

SUMMARY OF STAIN EFFICIENCIES

Case No.	E_i v/cm	E_c v/cm	Calc. Eff. %	Exp. Eff. %	Old Theory Calculation E_i v/cm	E_c v/cm	Eff. %
I	1763	9606	70.02	69.40	4803	9606	96.65
II	1763	9598	57.13	57.50	4799	9598	85.01
III	1763	9635	47.69	47.90	4817	9635	74.25
IV	1763	9619	43.20	38.10	4809	9619	67.79

Figure 17. Efficiency vs. flow rate (CFM).



CHAPTER VII

SUMMARY AND CONCLUSIONS

Residential parallel plate electrostatic precipitators have never been studied in sufficient depth. The Deutsch equation, based on turbulent flow and used to find the efficiency of industrial precipitators, appeared to have little application in a residential type laminar-flow precipitator. The ionization voltage gradient formula formerly used was found to give too high efficiency predictions for the corrugated plate Metal-Fab cell.

The visual flow pattern through the plates, along with the Reynolds Number calculated, proved the presence of laminar flow through the cell. Based on this criterion, an efficiency formula was derived using particle kinetics and ionization voltage gradient for parallel plates. From this efficiency formula it was possible to predict efficiencies that were comparable to the experimental values. Also, it was possible to predict efficiencies for various voltages, velocities and wire sizes.

Calculated efficiencies using the old theory were based on the ionizing voltage gradient found using the ratio of voltage to distance between wire and negative plate. Using the old theory yielded efficiencies that were much too high. The Teledeltos paper field plots showed a less steep voltage gradient at the wire for the Metal-Fab design than was intended for the old theory.

The results of this study prove the existence of laminar flow in residential electrostatic precipitators at normal air flows, and findings provide an accurate and reliable tool to study and evaluate this type of precipitator. The efficiency formula developed allows one to predict the efficiency at various voltages, flow rates, and wire sizes for a range of particle diameters.

This study determined the flow pattern and found a relationship for efficiency prediction over a limited range of variation. Obviously, a broader range of voltages and ionization currents should be tested. The exact behavior of particles around the curvature of the plates should be studied more precisely, with the derived formula being tested on straight plate cells.

LITERATURE CITED

1. White, H. J., "Fifty Years of Electrostatic Precipitation," Air Pollution Control Association Proceedings, pp. 49-50, 1956-57.

2. White, H. J., Industrial Electrostatic Precipitation, Addison-Wesley Publ. Co., Inc., 1963.

3. Penney, G. W., "Electrical Precipitation for Air-Conditioning Applications," Electrical Precipitation Fundamentals, The Pennsylvania State University, July 1961.

4. Penney, G. W. and Niedra, Janis M., "Orientation and the Adhesion of Particles," IEEE Trans., Vol. IECI-12, No. 2, pp. 46-50, Nov. 1965.

5. Penney, G. W. and Seman, G. W., "Photographic Records of Particle Trajectories During Electrostatic Precipitation," IEEE Convention Record, pt. 7, pp. 69-72, 1965.

6. Penney, G. W. and Seman, G. W., "Photographic Studies of Particle Behavior under Varying Precipitation Conditions," IEEE Trans., Vol. PAS-86, No. 3, March 1967.

7. Penney, G. W., "Electrostatic Precipitation Studies at Carnegie Institute of Technology," Journal of Air Pollution Control Association, Vol. 17, No. 9, Sept. 1967, pp. 588-589.

8. Penney, G. W., "Electrostatic Precipitation of High Resistive Dust," AIEE Transactions, 1951, Vol. 70, pp. 1192-1196.

9. Oglesby, Sabert, et al., A Manual of Electrostatic Precipitator Technology - Part I - Fundamentals, U. S. Department of Commerce, National Technical Information Service, Southern Research Institute, Aug. 25, 1970.

10. Penney, G. W., "Some Problems in the Application of the Deutsch Equation to Industrial Electrostatic Precipitation," Journal of Air Pollution Control Association, Aug. 1969, Vol. 19, No. 8, pp. 596-600.

11. Knudsen, J. G. and Katz, D. C., Fluid Dynamics and Heat Transfer, McGraw-Hill, New York, 1958, p. 105.

12. Whitby, K.T., unpublished report, 1956, U. of Minnesota,Fine Particle Lab.

13. Stern, A.C., Air Pollution, Vol.III, Academic Press, 1968; ch. 45 by Gottschlich, Chad F., "Electrostatic Precipitation."

14. Troost, N., "A New Approach to the Theory - An Operation of Electrostatic Precipitators for Use on Pulverized-Fuel-Fired Boilers," Proc. Inst. Elect. Engrs., London, Part II, 1954, p. 369.

15. Whitby, K. T., Algren, A. B. and Jordan, R. C. "The ASHAE Air Borne Dust Survey," Heating, Piping and Air Conditioning, Nov. 1957, p. 185.

16. Whitby, K. T., Algren, A. B. and Jordan, R. C. "Aspects of Air Cleaner Performance and Related Problems," Technical Report No. 3, Fine Particle Laboratory, University of Minnesota.

17. Reif, A. E., Aviation Medicine, AGARDograph 25: Aerosols-Physical Properties, Instrumentation and Techniques, Pergamon Press, 1958, p. 176.

BIBLIOGRAPHY

Cooperman, P., "A Theory for Space-Charge-Limited Currents with Application to Electrical Precipitation," AIEE, March 1960, pp. 47-50.

Faith, Larry E. and others, "Particle Precipitation by Space Charge in Tubular Flow," I & EC Fundamentals, Vol. 6, No. 4, November 1967, pp. 519-526.

Gillespie, T., "The Role of Electric Forces in the Filtration of Aerosols by Fiber Filters," University of London, Dec. 1, 1954, Revised April 12, 1955.

Heinrich, Thürmer, "Investigation with the Horizontal Plate Precipitator," Staub-Reinhalt Luft, Vol. 29, No. 12, December 1969, pp. 35-42.

Hewitt, G. W., "The Charging of Small Particles for Electrostatic Precipitation," AIEE Trans., July 1957, pp. 300-306.

Kraemer, Herbert F. and Johnstone, H. F., "Collection of Aerosol Particles in Presence of Electrostatic Fields," Industrial and Engineering Chemistry, Vol. 47, No. 14, 1955.

Lowe, H. J. and Lucas, D. H., "The Physics of Electrostatic Precipitation," British Journal of Applied Physics, Supplement No. 2.

Penney, Gaylord W., "Electrostatic Precipitation," Mechanical Engineering, October 1968, pp. 32-33.

Penney, G. W., "A New Electrostatic Precipitator," Mechanical Engineering, January 1937, pp. 159-163.

Penney, G. W. and Hewitt, G. W., "Electrically Charged Dust in Room," AIEE Trans., 1949, Vol. 68, pp. 278-282.

Penney, G. W. and Lynch, Robert D., "Measurements of Charge Imparted to Fine Particles by a Corona Discharge," AIEE Trans., July 1957, pp. 294-299.

Robinson, Myron, "Turbulent Gas Flow and Electrostatic Precipitation," Journal of the Air Pollution Control Association, April 1968, Vol. 18, No. 4, pp. 235-239.

Robinson, Myron, "A Modified Deutsch Efficiency Equation for Electrostatic Precipitation," Atmospheric Environment, Pergamon Press, 1967, Vol. 1, Printed in Great Britain, pp. 193-204.

Townsend, John S., "The Potentials Required to Maintain Current between Coaxial Cylinders," Phil. Mag., (6) 28, 83, 1914.

Vincent, J. H., "Electrostatic Precipitation of Airborne Charged Dust Particles Trapped in Stationary or Quasi-Stationary Vortices," Atmospheric Environment, Pergamon Press, Vol. 5, Printed in Great Britain, 1971, pp. 791-799.

Whitby, K. T. and Liu, B. Y. H., "The Electrical Behaviour of Aerosols," Aerosol Science, Academic Press, London and New York, 1966.

Whitby, K. T., Algren, A.B., Jordan, and Annis, J. C., "Evaluation of Air Cleaners for Air Conditioning and Ventilation: Part 1-Apparatus," Heating, Piping and Air Conditioning, ASHAE Journal, Section 30, May 1958, pp. 171-178.

White, H. J., "Particle Charging in Electrostatic Precipitation," AIEE Trans., 1951, Vol. 70, pp. 1186-1191.

White, H. J. and Baxter, Walter A., Jr., "Electrostatic Precipitators, Mechanical Engineering, May 1960, pp. 54-56.

NOMENCLATURE

A = area of collecting surface

A_i (i = 1-5) = front area of cell

b = spacing between plates

C = Cunningham coefficient

c = constant of integration

d = spacing between discharge and plate electrode

D_p = particle diameter

E = electric field

E_c = electric field of collecting section

Eff. = stain efficiency

E_i = electric field of ionizing section

F_e = electrical force

F_g = gravitational force

F_i = inertia force

F_η = viscous force

g = acceleration of gravity

h = average spacing between discharge electrodes

i = electrical current per unit length of the discharge electrode

K = ion mobility, m^2/v-sec.

K_0 = dielectric constant of vacuum, 8.85434×10^{-12} coul.^{2}/Joules-m

m = particle mass

N_{Re} = Reynolds Number

Q = volume rate of air flow

q = particle charge

r = radial distance measured from the centerline of the discharge electrode, amp/m

R_1 = discharge electrode radius, meters

R_2 = collecting electrode radius, meters

s = distance between positive and negative plates

t = time

t_1 = time to travel 10.16 cm.

t_s = time to travel 0.635 cm.

u = particle velocity

u_x = particle velocity in x-direction

u_y = particle velocity in y-direction

U = average velocity

v = drift velocity

v_g = gas velocity

V = voltage difference between the electrodes, volts

V_i (i = 1-5) = air velocity through A_i

x = maximum horizontal distance required to stop

y = maximum distance from the collecting plate to most distant particle which could be collected

Z = particle mobility

μ = micron

μ_f = fluid viscosity

ρ_p = particle density

ρ_g = gas density

η = efficiency

APPENDIX A

OLD THEORY STAIN EFFICIENCY CALCULATIONS

Example Calculation (Q = 512 cfm)

E_i = 6118 volts

E_c = 6118 volts

Charge on Particle:

$$q = E_i^{0.59} D_p^{0.162 \ln(4.31 E_i)}$$

E_i = 6118 volts/(0.5 in)(2.54 cm/in) = 4817 v/cm

$$q = (4817)^{0.59} D_p^{0.162 \ln(4.31)(4817)}$$

$$q = 149 D_p^{1.6104}$$

Collection Mechanism:

$$u_y = \frac{1.6 \times 10^{-12} q E_c C}{3\pi\mu_g D_p}$$

E_c = 6118 volts/(0.25 in)(2.54 cm/in) = 9635 v/cm

$$u_y = \frac{1.6 \times 10^{-12}(149 D_p^{1.6104})(9635 \text{ v/cm}) C}{3\pi(1.88 \times 10^{-4}) D_p(10^{-4} \text{ cm}/\mu)}, \quad D_p \text{ in microns}$$

$$u_y = 12.96 D_p^{0.6104} C$$

Time to travel 0.635 cm, t_s:

$$t_s = \frac{0.635 \text{ cm}}{12.96 D_p^{0.6104} C} = 0.04900 D_p^{-0.6104} C^{-1}$$

Time to travel 4 in.(10.16 cm.) horizontally, t_1:

$$t_1 = \frac{x}{V} = \frac{10.16 \text{ cm}}{330 \text{ cm/sec}}$$

where:

x = plate length

V = particle velocity

$$V = \frac{512 \text{ ft}^3/\text{min}}{0.788 \text{ ft}^2} \left(\frac{0.5085 \text{ cm/sec}}{1 \text{ ft/min}}\right)$$

$$V = 330 \text{ cm/sec}$$

Filtration Efficiency, Eff. = $t_1/t_s = \dfrac{0.0308\, D_p^{0.6104}\, C}{0.0490}$

$$\text{Eff.} = 0.629\, D_p^{0.6104}\, C \qquad (\text{if} > 1, \text{use } 1)$$

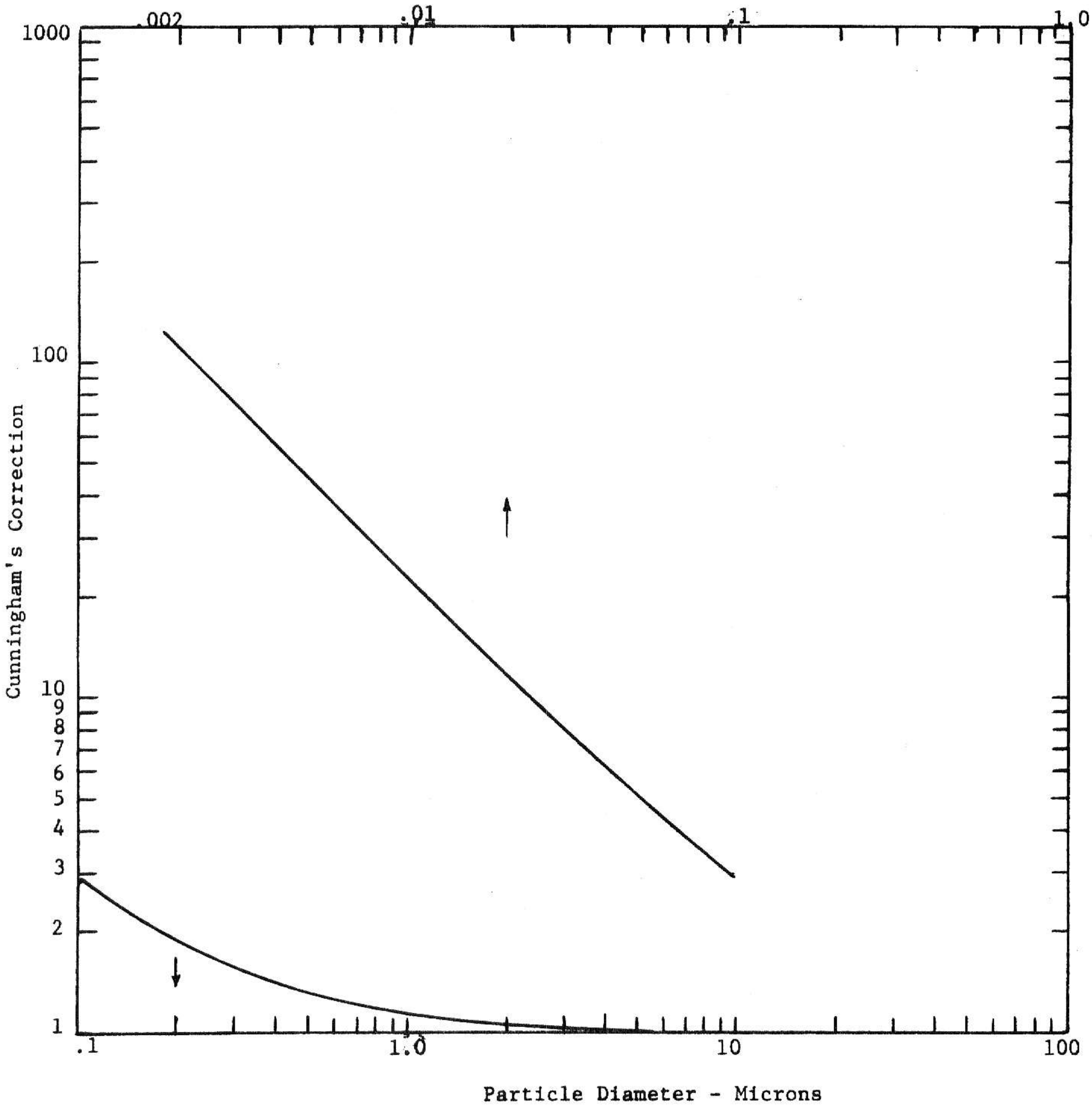


Figure 18. Cunningham's correction vs. particle size [17].

Figure 19. Diffraction by opaque particles for various semi-angles of acceptance of the measuring photocell after Davies.

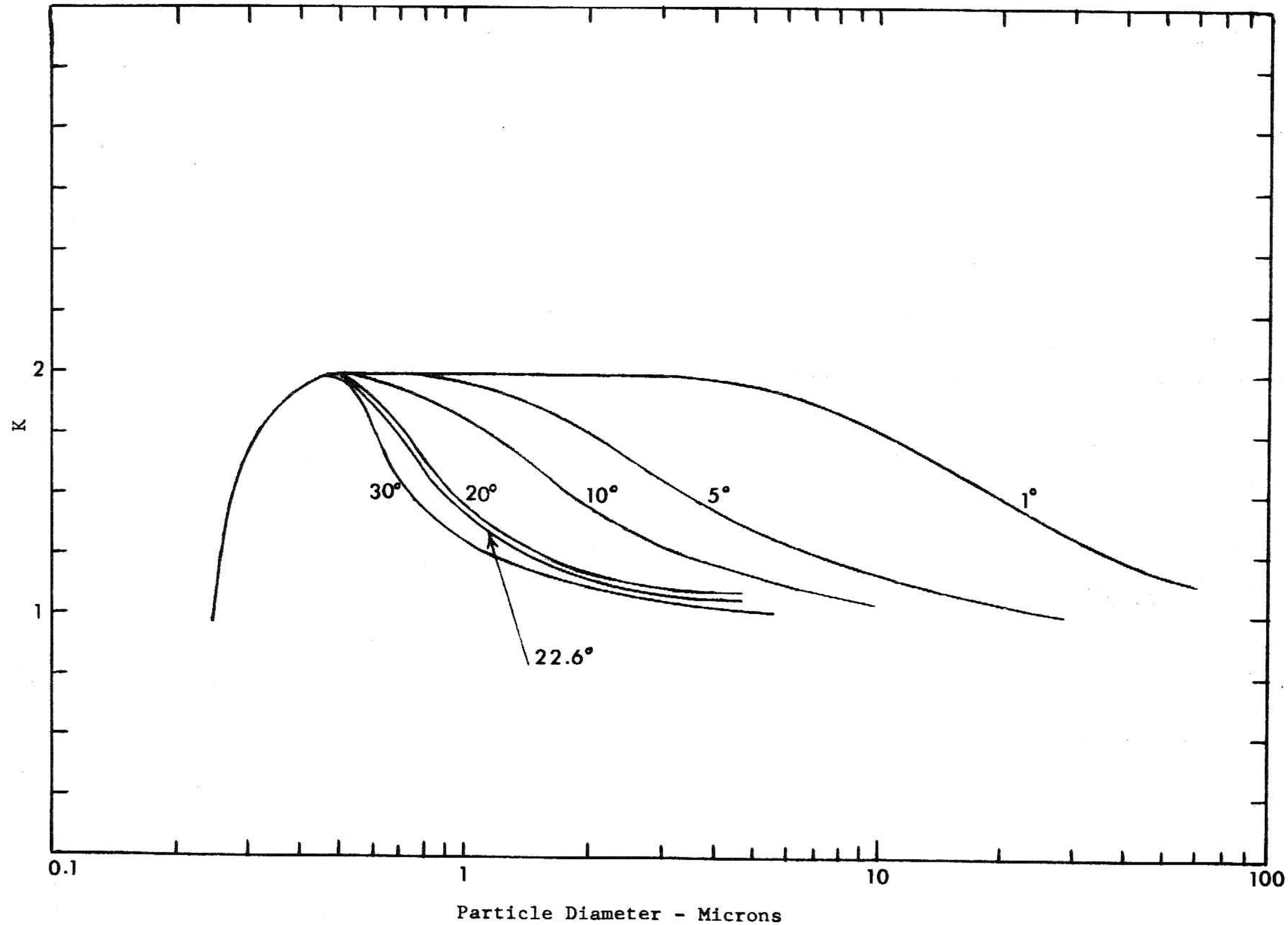


TABLE 3

ATMOSPHERIC DUST DISTRIBUTION

I. B.	Mid point D_p-μ	$\frac{\sum_1^i n_i D_p^3}{\sum_1^n n_i D_p^3}$	$\frac{n_i D_p^3}{\sum_{i=1}^n n_i D_p^3}$	$n_i D_p^3$	$n_i D_p^2$	From Davies Curve K_i	$n_i D_p^2 K$	$\sum_{i=1}^i n_i D_p^2 K$	$\frac{\sum_1^i n_i D_p^2 K}{\sum_1^n n_i D_p^2 K}$
0.32	0.16	0.010	0.01	1.00	6.25	0.23	1.44	1.44	0.021
0.56	0.44	0.050	0.04	4.00	9.10	1.97	17.93	19.37	0.282
0.83	0.69	0.100	0.05	5.00	7.25	1.75	12.69	32.06	0.467
1.40	1.12	0.200	0.10	10.00	8.93	1.35	12.06	44.12	0.642
1.80	1.60	0.300	0.10	10.00	6.25	1.21	7.56	51.68	0.753
2.50	2.15	0.400	0.10	10.00	4.65	1.14	5.30	56.98	0.830
3.30	2.90	0.500	0.10	10.00	3.45	1.10	3.80	60.78	0.885
4.40	3.85	0.600	0.10	10.00	2.60	1.08	2.81	63.59	0.926
5.80	5.10	0.700	0.10	10.00	1.96	1.05	2.06	65.65	0.956
8.00	6.90	0.800	0.10	10.00	1.45	1.02	1.48	67.13	0.978
13.00	10.50	0.900	0.10	10.00	0.95	1.00	0.95	68.08	0.991
16.00	14.50	0.950	0.05	5.00	0.34	1.00	0.34	68.42	0.996
21.00	18.50	0.911	0.041	4.10	0.22	1.00	0.22	68.64	0.9996
26.00	23.50	0.998	0.007	0.70	0.03	1.00	0.03	68.67	1.0000

TABLE 4

CALCULATED EFFICIENCIES BASED ON 300 CFM

Percentile* mid points	D_p-μ	$D^{0.6101}$	C**	Stain Eff.) calc.	Stain Eff.) actual
95	5.50	2.833	1.03	3.123	1.000
85	2.75	1.853	1.06	2.102	1.000
75	1.80	1.432	1.09	1.670	1.000
65	1.40	1.228	1.12	1.472	1.000
55	1.06	1.036	1.15	1.275	1.000
45	0.80	0.873	1.20	1.121	1.000
35	0.65	0.769	1.25	1.028	1.000
25	0.53	0.679	1.30	0.945	0.945
15	0.45	0.614	1.36	0.894	0.894
5	0.36	0.536	1.44	0.826	0.826
				Total	9.665
				Efficiency	96.65%

* Stain size distribution

** Cunningham corrections from Fig. 18.

TABLE 5

CALCULATED EFFICIENCIES BASED ON 405 CFM

Percentile* mid points	D_p-μ	$D^{0.6100}$	C**	Stain Eff.) calc.	Stain Eff.) actual
95	5.50	2.830	1.03	2.306	1.000
85	2.75	1.852	1.06	1.553	1.000
75	1.80	1.431	1.09	1.234	1.000
65	1.40	1.228	1.12	1.088	1.000
55	1.06	1.036	1.15	0.942	0.942
45	0.80	0.873	1.20	0.829	0.829
35	0.65	0.769	1.25	0.760	0.760
25	0.53	0.679	1.30	0.698	0.698
15	0.45	0.614	1.36	0.661	0.661
5	0.36	0.536	1.44	0.611	0.611
				Total	8.501
				Efficiency	85.01%

* Stain size distribution.

** Cunningham corrections from Fig. 18.

TABLE 6

CALCULATED EFFICIENCIES BASED ON 512 CFM

Percentile* mid points	D_p-μ	$D^{0.6104}$	C**	Stain Eff.) calc.	Stain Eff.) actual
95	5.50	2.833	1.03	1.835	1.000
85	2.75	1.853	1.06	1.235	1.000
75	1.80	1.432	1.09	0.982	0.982
65	1.40	1.228	1.12	0.865	0.865
55	1.06	1.036	1.15	0.750	0.750
45	0.80	0.873	1.20	0.659	0.659
35	0.65	0.769	1.25	0.604	0.604
25	0.53	0.679	1.30	0.555	0.555
15	0.45	0.614	1.36	0.525	0.525
5	0.36	0.536	1.44	0.485	0.485
				Total	7.425
				Efficiency	74.25%

* Stain size distribution.

** Cunningham corrections from Fig. 18.

TABLE 7

CALCULATED EFFICIENCIES BASED ON 580 CFM

Percentile* mid points	D_p-μ	$D^{0.6102}$	C**	Stain Eff.) calc.	Stain Eff.) actual
95	5.50	2.833	1.03	1.617	1.000
85	2.75	1.853	1.06	1.088	1.000
75	1.80	1.432	1.09	0.865	0.865
65	1.40	1.228	1.12	0.762	0.762
55	1.06	1.036	1.15	0.660	0.660
45	0.80	0.873	1.20	0.580	0.580
35	0.65	0.769	1.25	0.532	0.532
25	0.53	0.679	1.30	0.489	0.489
15	0.45	0.614	1.36	0.463	0.463
5	0.36	0.536	1.44	0.428	0.428
				Total	6.779
				Efficiency	67.79%

* Stain size distribution.

** Cunningham corrections from Fig. 18.

TABLE 8

SUMMARY OF EFFICIENCY CALCULATIONS BY THE OLD THEORY

Case No.	Q cfm	E_i	E_c	Stain Eff.	Stain Eff. %
I	300	4803	9606	0.9665	96.65
II	405	4799	9598	0.8501	85.01
III	512	4817	9635	0.7425	74.25
IV	580	4809	9619	0.6779	67.79

APPENDIX B

NEW THEORY EFFICIENCY CALCULATIONS

Assumed Criteria

The length of plates were considered to be 13.3 in. Although only every fourth plate was 4 in. deep, the effective collecting length was considered 4 in. because it was the weighted average of the plate depths. (50% 3.5-in. plates; 25% 5-in. plates; 25% 4-in. plates.)

The cumulative volume-weighted particle size of Whitby [15] along with Davis' [16] light scattering coefficients for opaque particles were used to determine the stain distribution curve of Fig. 16. From observation of precipitator cells, it was concluded that about 0.5 in. on each side of the plates was not collecting and, therefore, it was assumed to be ineffective in determining the velocity of charged particles. Areas calculated under various assumptions are:

$A_1 = 13.3 \times 10.2 = 135.66 \text{ in.}^2 = 0.942 \text{ ft}^2$

$A_2 = 13.3(10.2 - 39(0.023)) = 123.73 \text{ in.}^2 = 0.859 \text{ ft}^2$

$A_3 = 13.3(10.2 - 39(0.047)) = 111.28 \text{ in.}^2 = 0.773 \text{ ft}^2$

$A_4 = (13.3 - 2(0.5))(10.2) = 125.46 \text{ in.}^2 = 0.871 \text{ ft}^2$

$A_5 = 0.942 - (0.942 - 0.859) - (0.942 - 0.871) = 0.788 \text{ ft}^2$

where A_1, A_2, etc. are defined as in Table

Collecting depth = 4 in. = 10.16 cm.

Plate spacing = 0.25 in. = 0.635 cm.

Plate thickness = 0.023 in.

Thickness of folding edge = 0.047 in.

Reynolds Number Calculation:

$$N_{Re} = \frac{2\ b\ U\rho_g}{\mu_g}$$

where:

b = plate spacing

U = average velocity

ρ_g = density

μ_g = gas viscosity

cross-sectional area = 0.25 in. x 14 in. = 3.5 in.^{2} = 0.0243 ft^2

$$Q_{max} = \frac{580 \text{ cfm}}{40 \text{ sections}} = 14.5 \text{ cfm in. each section}$$

$$U = \frac{14.5 \text{ cfm/section}}{0.0243 \text{ ft}^2\text{/section}} = 596.71 \text{ ft/min} = 303.13 \text{ cm/sec}$$

using air at 75 degree F, 50% R.H. and 29 in. of H_2O

$\mu_g = 1.88 \times 10^{-4}$ gm/cm-sec

$\rho_g = 1.15 \times 10^{-3}$ gm/cm^3

$$N_{Re} = \frac{(2 \times 0.25 \text{ in.} \times 2.54 \text{ cm/in.})(303.13 \text{ cm/sec})(1.15 \times 10^{-3} \text{ gm/cm}^3)}{1.88 \times 10^{-4} \text{ gm/cm-sec}}$$

N_{Re} = 2355

TABLE 9

VELOCITY CALCULATIONS

Area ft^2	Velocity cm/sec	580 CFM	530 CFM	512 CFM	405 CFM	400 CFM	300 CFM
0.942	V_1	313	286	276	218	216	162
0.859	V_2	343	313	303	240	237	177
0.773	V_3	381	348	336	266	263	197
0.871	V_4	338	309	299	236	233	175
0.788	V_5	374	342	330	261	258	193

V_1 is based on front area not considering plate thickness or dead areas.

V_2 is based on front area less plate thickness.

V_3 is based on front area less thickness of folding edge.

V_4 is based on front area less dead area on each side of plates (0.5 inches used on each side).

V_5 is based on front area less plate thickness, less dead area on each side of plates.

TABLE 10

SUMMARY OF EXPERIMENTAL DATA

Case No.	Run No.	CFM	Stain Eff.	Avg. Eff.	Current mili-amp	Avg. Current	Voltage (volts)	Avg. Voltage	Remarks
I	19	300	69.6		0.40		6100		10 wires
	20	300	69.1	69.4	0.40	0.40	6100	6100	7 mil dia. YA34
II	10	405	62.8		0.40		6125		10 wires
	11	405	57.7		0.40		6100		7 mil dia.
	12	405	56.7		0.40		6055		YA34
	21	405	58.2	57.7	0.40	0.40	6100	6095	
III	6	512	53.6		0.40		6135		10 wires
	7	512	46.0		0.40		6135		7 mil dia.
	13	512	45.9		0.40		6100		YA34
	22	512	46.1	47.9	0.40	0.40	6100	6118	

TABLE 10 (cont'd)

Case No.	Run No.	CFM	Stain Eff.	Avg. Eff.	Current mili-amp	Avg. Current	Voltage volts	Avg. Voltage	Remarks
IV	8	580	42.4		0.40		6125		10 wires
	9	580	31.1		0.40		6105		7 mil dia.
	18	580	38.3		0.40		6100		YA34
	23	580	40.7	38.1	0.40	0.40	6100	6108	
V	74	300	75.0		2.32		6065		48 wires
	75	300	75.9		2.29		6070		6 mil dia.
	76	300	75.9	75.6	2.29	2.30	6070	6068	4-YA34's, 1-YA32
VI	66	300	78.9		2.22		6105		40 wires
	67	300	79.0		2.21		6110		6 mil dia.
	68	300	78.4		2.24		6045		4-YA34's
	69	300	81.3		2.25		6100		
	70	300	80.8		2.28		6080		
	71	300	79.5	79.65	2.20	2.23	6135	6095	

TABLE 10 (cont'd)

Case No.	Run No.	CFM	Stain Eff.	Avg. Eff.	Current mili-amp	Avg. Current	Voltage volts	Avg. Voltage	Remarks
VII	77	300	75.1		1.95		6215		32 wires
	78	300	81.4		1.96		6215		6 mil dia.
	79	300	80.5		1.96		6215		2-YA34's
	80	300	79.6	79.15	1.93	1.95	6225	6218	1-YA36
VIII	63	300	77.0		1.83		6270		40 wires
	64	300	80.3		1.87		6245		7 mil dia.
	65	300	76.6	77.97	1.89	1.86	6235	6250	4-YA34's
IX	81	300	82.3		1.60		6110		24 wires
	82	300	83.6		1.63		6350		6 mil dia.
	83	300	83.9	83.27	1.66	1.63	6330	6263	1-YA34, 2-YA31's

TABLE 11

SUMMARY OF EXPERIMENTAL DATA, CASES I-IX

Case No.	I	II	III	IV	V	VI	VII	VIII	IX
No. of wires	10	10	10	10	48	40	32	40	24
Wire size	7 mil	7 mil	7 mil	7 mil	6 mil	6 mil	6 mil	7 mil	6 mil
Voltage (volts)	6100	6095	6118	6108	6068	6095	6218	6250	6263
Current (mili-amp)	0.40	0.40	0.40	0.40	2.30	2.23	1.95	1.86	1.63
i (amp/m)	1.21×10^{-4}	1.21×10^{-4}	1.21×10^{-4}	1.21×10^{-4}	1.45×10^{-4}	1.69×10^{-4}	1.85×10^{-4}	1.41×10^{-4}	2.06×10^{-4}
E_c -v/cm	9606	9598	9635	9619	9556	9598	9792	9843	9863
E_i -v/cm	1763	1763	1763	1763	1932	2083	2179	1903	2300

Example Calculations (Case VI)

$$E_i = \sqrt{\frac{2\ i\ d}{\pi K_0 K\ h}}$$

where:

$$i = \frac{2.23 \text{ mili-amp} \times 10^{-3} \text{ amp/mili-amp}}{4 \text{ cells} \times 10 \text{ wires/cell} \times 13 \text{ in./wire}}$$

$$= \frac{2.23 \times 10^{-3} \text{ amp}}{520 \text{ in.}}$$

$$= 1.689 \times 10^{-4} \text{ amp/m}$$

$$E_i = \sqrt{\frac{2 \times 1.689 \times 10^{-4} \times 0.5 \text{ in.} \times 0.0254 \text{ m/in.}}{\pi \times 8.85434 \times 10^{-12} \times 1.4 \times 1 \text{ in.} \times 0.0254 \text{ m/in.}}}$$

$$= 2083 \text{ v/cm}$$

$$E_c = \frac{\text{voltage}}{\text{plate spacing}} = \frac{6175}{0.635}$$

$$= 9598 \text{ v/cm}$$

$$\text{Eff.} = \frac{(1.446 \times 10^{-4})\ C\ E_c\ (E_i^{0.59}\ D_p^{0.162} \ln(4.31)(E_i)}{V\ D_p}$$

$$\text{Eff.} = \frac{(1.446 \times 10^{-4})\ C\ (9598)(2083^{0.59}\ D_p^{0.162} \ln(4.31)(2083))}{193\ D_p}$$

Efficiency calculation for $D_p = 5.5$ and $C = 1.02$:

$$\text{Eff.} = \frac{(1.446 \times 10^{-4})(1.02)(9598)(90.79)(5.5)^{0.162(1.46 + 7.6)}}{(193)(5.5)}$$

$\text{Eff.})_{\text{calc.}} = 1.481$

$\text{Eff.})_{\text{actual}} = 1.000$

Cases I, II, III, IV

$$i = \frac{0.40 \times 10^{-3}}{10 \times 0.33} = 1.21 \times 10^{-4} \text{ amp/m}$$

$$E_i = 1.603 \times 10^5 \sqrt{i} = 1763 \text{ v/cm}$$

$$E_{c_I} = \frac{6100}{0.635} = 9606 \text{ v/cm}$$

$$E_{c_{II}} = \frac{6095}{0.635} = 9598 \text{ v/cm}$$

$$E_{c_{III}} = \frac{6118}{0.635} = 9635 \text{ v/cm}$$

$$E_{c_{IV}} = \frac{6108}{0.635} = 9619 \text{ v/cm}$$

$$\text{Eff.} = \frac{1.19 \times 10^{-2} \text{ C } D_p^{0.77}}{V}$$

Cases I, II, III, IV

Case No.				I	II	III	IV
E_c, v/cm				9606	9598	9635	9616
V, cm/sec				193	261	330	374
D_p	$D_p^{0.77}$	C	1.19×10^{-2} C	Eff.	Eff.	Eff.	Eff.
5.5	3.716	1.02	1.21×10^{-2}	1.000	1.000	1.000	1.000
2.75	2.179	1.07	1.29×10^{-2}	1.000	1.000	0.821	0.723
1.80	1.572	1.10	1.31×10^{-2}	1.000	0.757	0.601	0.530
1.40	1.296	1.11	1.32×10^{-2}	0.851	0.629	0.499	0.440
1.06	1.046	1.15	1.37×10^{-2}	0.713	0.527	0.418	0.369
0.80	0.842	1.20	1.43×10^{-2}	0.599	0.443	0.352	0.310
0.65	0.718	1.25	1.49×10^{-2}	0.532	0.393	0.312	0.275
0.53	0.613	1.30	1.55×10^{-2}	0.473	0.349	0.277	0.244
0.45	0.541	1.38	1.64×10^{-2}	0.442	0.326	0.259	0.228
0.36	0.455	1.45	1.73×10^{-2}	0.392	0.289	0.230	0.202
			Total	7.002	5.713	4.769	4.320
			Stain Efficiency	70.02%	57.13%	47.69%	43.20%

Case V

$$i = \frac{2.30 \times 10^{-3}}{48 \times 0.33} = 1.452 \times 10^{-4} \text{ amp/m}$$

$$E_i = 1.603 \times 10^5 \sqrt{i} = 1932 \text{ v/cm}$$

$$E_c = \frac{6068}{0.635} = 9556 \text{ v/cm}$$

$$V = 300 \text{ cfm} = 193 \text{ cm/sec}$$

$$\text{Eff.} = \frac{1.26 \times 10^{-2}\, E_c\, C\, D_p^{0.46}}{V}$$

Percentile mid points	D_p	$D_p^{0.46}$	$C\ D_p^{0.46}$	Stain Eff.)$_{calc.}$	Stain Eff.)$_{actual}$
95	5.50	2.191	2.235	1.394	1.000
85	2.75	1.593	1.705	1.063	1.000
75	1.80	1.310	1.441	0.899	0.899
65	1.40	1.167	1.295	0.808	0.808
55	1.06	1.027	1.181	0.737	0.737
45	0.80	0.902	1.082	0.675	0.675
35	0.65	0.820	1.025	0.639	0.639
25	0.53	0.747	0.971	0.606	0.606
15	0.45	0.693	0.956	0.597	0.597
5	0.36	0.625	0.906	0.565	0.565

Total 7.526

Efficiency 75.26%

Case VI

$$i = \frac{2.23 \times 10^{-3}}{40 \times 0.33} = 1.689 \times 10^{-4} \text{ amp/m}$$

$$E_i = 1.603 \times 10^5 \sqrt{i} = 2083 \text{ v/cm}$$

$$E_c = \frac{6095}{0.635} = 9598 \text{ v/cm}$$

$$V = 300 \text{ cfm} = 193 \text{ cm/sec}$$

$$\text{Eff.} = \frac{1.31 \times 10^{-2} E_c \, C \, D_p^{0.47}}{V}$$

Percentile mid points	D_p	$D_p^{0.47}$	$C\ D_p^{0.47}$	Stain Eff.)$_{calc.}$	Stain Eff.)$_{actual}$
95	5.50	2.228	2.273	1.481	1.000
85	2.75	1.609	1.721	1.121	1.000
75	1.80	1.318	1.450	0.945	0.945
65	1.40	1.171	1.300	0.847	0.847
55	1.06	1.028	1.182	0.770	0.770
45	0.80	0.900	1.081	0.704	0.704
35	0.65	0.817	1.021	0.665	0.665
25	0.53	0.742	0.965	0.629	0.629
15	0.45	0.687	0.948	0.618	0.618
5	0.36	0.619	0.897	0.584	0.584

Total 7.762

Efficiency 77.62%

<u>Case VII</u>

$$i = \frac{1.95 \times 10^{-3}}{32 \times 0.33} = 1.847 \times 10^{-4} \text{ amp/m}$$

$$E_i = 1.603 \times 10^5 \sqrt{I} = 2179 \text{ v/cm}$$

$$E_c = \frac{6218}{0.635} = 9792 \text{ v/cm}$$

$$V = 300 \text{ cfm} = 193 \text{ cm/sec}$$

$$\text{Eff.} = \frac{1.35 \times 10^{-2} E_c \, C \, D_p^{0.48}}{V}$$

Percentile mid points	D_p	$D_p^{0.48}$	$C\ D_p^{0.48}$	Stain Eff.$)_{calc.}$	Stain Eff.$)_{actual}$
95	5.50	2.267	2.31	1.582	1.000
85	2.75	1.625	1.74	1.192	1.000
75	1.80	1.326	1.46	1.000	1.000
65	1.40	1.175	1.30	0.890	0.890
55	1.06	1.028	1.18	0.808	0.808
45	0.80	0.898	1.08	0.740	0.740
35	0.65	0.813	1.02	0.699	0.699
25	0.53	0.737	0.96	0.658	0.658
15	0.45	0.682	0.94	0.644	0.644
5	0.36	0.612	0.89	0.610	0.610

Total 8.049

Efficiency 89.49%

Case VIII

$$i = \frac{1.86 \times 10^{-3}}{40 \times 0.33} = 1.409 \times 10^{-4} \text{ amp/m}$$

$$E_i = 1.603 \times 10^5 \sqrt{i} = 1903 \text{ v/cm}$$

$$E_c = \frac{6250}{0.635} = 9843 \text{ v/cm}$$

$$V = 300 \text{ cfm} = 193 \text{ cm/sec}$$

$$\text{Eff.} = \frac{1.245 \times 10^{-2} E_c C D_p^{0.46}}{V}$$

Percentile mid points	D_p	$D_p^{0.46}$	$C D_p^{0.46}$	Stain Eff.)$_{calc.}$	Stain Eff.)$_{actual}$
95	5.50	2.191	2.234	1.418	1.000
85	2.75	1.593	1.704	1.082	1.000
75	1.80	1.310	1.442	0.916	0.916
65	1.40	1.167	1.296	0.823	0.823
55	1.06	1.027	1.181	0.750	0.750
45	0.80	0.902	1.083	0.688	0.688
35	0.65	0.820	1.025	0.651	0.651
25	0.53	0.747	0.971	0.616	0.616
15	0.45	0.693	0.956	0.607	0.607
5	0.36	0.625	0.906	0.575	0.575

Total 7.626

Efficiency 76.26%

Case IX

$$i = \frac{1.63 \times 10^{-3}}{24 \times 0.33} = 2.058 \times 10^{-4} \text{ amp/m}$$

$$E_i = 1.603 \times 10^5 \sqrt{i} = 2300 \text{ v/cm}$$

$$E_c = \frac{6263}{0.635} = 9863 \text{ v/cm}$$

$$V = 300 \text{ cfm} = 193 \text{ cm/sec}$$

$$\text{Eff.} = \frac{1.39 \times 10^{-2} E_c \, C \, D_p^{0.49}}{V}$$

Percentile mid points	D_p	$D_p^{0.49}$	$C\ D_p^{0.49}$	Stain Eff.$)_{calc.}$	Stain Eff.$)_{actual}$
95	5.50	2.306	2.352	1.671	1.000
85	2.75	1.642	1.757	1.248	1.000
75	1.80	1.334	1.467	1.042	1.000
65	1.40	1.179	1.309	0.930	0.930
55	1.06	1.029	1.183	0.840	0.840
45	0.80	0.896	1.076	0.764	0.764
35	0.65	0.810	1.012	0.719	0.719
25	0.53	0.733	0.952	0.676	0.676
15	0.45	0.676	0.933	0.663	0.663
5	0.36	0.606	0.879	0.624	0.624

Total 8.216

Efficiency 82.16%

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AN EFFICIENCY PREDICTION THEORY FOR A RESIDENTIAL, CORRUGATED PARALLEL PLATE ELECTROSTATIC PRECIPITATOR

by

MANSOUR MOJIBIAN

B. S., Kansas State University, 1970

AN ABSTRACT OF A MASTER'S THESIS

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This study was concerned with the derivation of an efficiency prediction theory for a residential, corrugated, parallel-plate electrostatic precipitator. The first phase was to study air flow characteristics in the parallel-plate section of the precipitator. The second phase was a study of variation in ionizing field about the ionizing wire. The final phase involved the development of a formula that would predict the stain efficiency for this type of precipitator.

The air flow study was performed using a wind tunnel with collector plates placed in the test section. By using a fine smoke stream it was possible to study the flow pattern. This test showed that the flow was laminar through the plates.

By using Teledeltos paper, the equal-potential lines of the ionizing field were plotted. The plots, with the field highest near the wire and decreasing as the distance from the wire increased, allowed better understanding of the variations in the field and showed a lower gradient near the wire than for usual two-stage units.

Calculated stain efficiencies from the developed formula agreed closely with the experimental values over a range of air velocities, voltages, and ionizing currents. Efficiencies calculated using the old theory for two-stage, residential units did not agree with the measured values. It is the voltage gradient of the ionizing section, as a function of the ionizing current, and its relationship to the charging mechanism that is of prime importance.