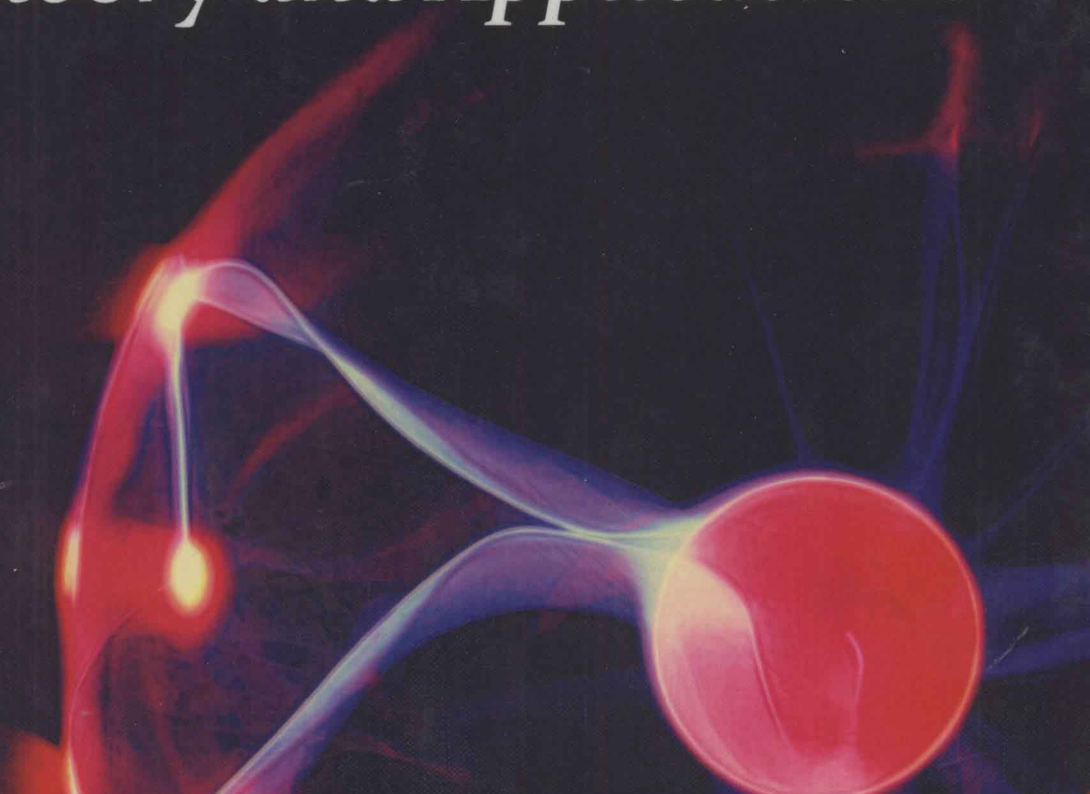
Camille L. Bertrand
Editor

Electrostatics
Theory and Applications



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ELECTROSTATICS: THEORY AND APPLICATIONS

CAMILLE L. BERTRAND
EDITOR

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ELECTROSTATICS: THEORY AND APPLICATIONS

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PREFACE

Electrostatics is the branch of science that deals with the phenomena arising from stationary or slow-moving electric charges. Electrostatic phenomena arise from the forces that electric charges exert on each other and include many examples, from the apparently spontaneous explosion of grain silos, to the damage of electronic components during manufacturing, to the operation of photocopiers. Among other topics, this book reviews research on asymmetric electrostatic forces and new electrostatic generators; the food industry's electrostatic powder coating, electrostatic capacitance extraction of arbitrary-shaped conducting bodies and the electrostatics of planar systems of conducting strips.

It is well known that there are three kinds of electrostatic force: gradient force, image force, and Coulomb force. A gradient force acts on a non-charged body that is placed in a convergent electric field. An image force acts on a charged body placed near a conductive plate. A Coulomb force acts on a charged body placed in an electric field. As for the shape of these bodies, only symmetric forms have been treated in the past. The representative example for all three force types is a sphere. Forty years ago, only the potential of a spherical body could be calculated. In contrast, today, we can calculate the potential of any shape by computer simulation.

In Chapter 1, a simulation of the electrostatic force that acts on asymmetrically shaped conductors is carried out. As a result, three interesting phenomena were found.

Firstly, it is assumed that the gradient force arises only in a convergence electric field, but the simulation herein demonstrated that the same force acts on an asymmetric conductor in a parallel electric field. I call this force the Asymmetric Force (AF).

Secondly, it is thought that, when any face of a charged conductor is pointed toward a conductive plate, the image force remains the same. However, the simulation showed that the image force exerted on an asymmetric conductor changes when different faces are pointed toward a conductive plate. I call this force the Asymmetric Image Force (AIF).

Thirdly, it is commonly believed that, if the direction of an electric field is reversed, the absolute value of the Coulomb force remains the same. However, the simulation demonstrated that the absolute value of the Coulomb force on an asymmetric conductor changes when the direction of the electric field is reversed. I call this force the Asymmetric Coulomb force (ACF).

In this work, a simulation and an experiment of the AF, a simulation of the AIF, and a simulation and an experiment of the ACF are presented.

New static electricity applications that use these three asymmetric forces are expected to develop. In particular, an electrostatic generator utilizing the ACF is promising. Thus, I present a concrete design and a prospective performance of this electrostatic generator. It is expected that the earth environmental problem and the energy crisis can be simultaneously solved with this new electrostatic generator.

Finally, I will introduce an unusual phenomenon in which the direction of the ACF does not change, even if the electric field surrounding the asymmetric charged conductor is reversed. This unusual phenomenon is made possible by appropriately designing the shape of the conductor; thus, it resembles the phenomenon in which a yacht can advance diagonally in a head wind.

Chapter 2 is a brief review of the investigations devoted to polymer film changes initiated by corona treatment and their possible applications. Polymer films, among which are polypropylene, polyethylene terephthalate and polytetrafluoroethylene, are most widely used as materials for the production of stable charged films. One of the simplest and most widespread methods for charging the polymers involves the use of corona discharge in air at room temperature. The corona discharge creates high energy oxygen-containing charged particles, which are accelerated by the electric field of the corona and then interact with the surface of the polymer films.

Firstly, changes in electret surfaces initiated by corona treatment, which are analyzed by XPS and an optical method, are discussed. The XPS investigations show that oxygen content in negative corona charged samples is several times higher than the ones of positive corona charged samples. The optical method of disappearing diffraction pattern is proposed to determine the surface modifications of the charged polymer films. The strongest surface modification is observed at the center of the samples and they are greatly affected by the applied corona voltage and the corona device configuration. The electric charges are mainly deposited onto the surface and do not penetrate into the sample bulk when corona charged films are formed under not very strong charging conditions (air ambient, room temperature and humidity, 5kV corona voltage).

Secondly, the influence of different treatments (low pressure and low-energy laser irradiation) on charged polymer film stability and its possible applications are discussed. The sharp surface potential decay in charged films stored under pressure lower than atmospheric down to 0.1mbar is observed. It is possible to calculate pressure at which sharp decay occurs if the initial surface potential is known. Preliminarily placing the charged films under pressure less than 1mbar can be used as a method for stabilizing the surface charge. The different surface potential decay and the relevant steady state surface potential values for charged films being under different irradiation conditions (continuous He-Ne, pulsed CuBr and quasi-continuous CO_2 lasers) are revealed. These results can find applications in optical storage and processing of information as a direct registration of information on electret films using low energy lasers.

Thirdly, the influence of corona treatment on holographic recording in photopolymer films is discussed. An additional inducted polarizability, which is due to an electric charging, influences the exposure characteristics and diffraction efficiency of the holographic recordings in amorphous side-chain azobenzene polymers. The additional electric corona charging seems to be a promising method for increasing both the diffraction efficiency and the sensitivity of the azo-polymer recording media.

The behavior of charged particles in turbulent gas flow in electrostatic precipitators (ESPs) is crucial information needed to design and optimize electrostatic precipitators, so a three-dimensional numerical simulation was performed to predict electrostatic fields, electro-hydrodynamic (EHD) turbulent flow and particle charging and tracing in a wire-plate ESP. For electrostatic field, the traditional finite difference method (FDM) has been widely applied to calculate two-dimensional electrical field in the wire-plate ESP on the base of the symmetry assumption. In Chapter 3 we analyze the reason why the traditional FDM method by Leutert and McDonald only converges in the first quadrant of single discharge electrode, and we give the numerical method suitable to obtain a convergence solution in the other quadrants. Based on an analogy between the electric equation and the fluid dynamics equation, we propose the upwind (or downwind) scheme to calculate the electrostatic field in the case of positive (or negative) corona. For EHD flow, the classic k-ε model is applied to describe the EHD turbulent flow in a wire-plate ESP, and a non-dimensional EHD number is introduced to analyze the interactions between the cross-flow and the electric wind. The electric wind has the arrays of large-scale, spanwise counter-rotating vortical structures, and three different types of singularities are located at equally spaced intervals. On average, each wire generates four equal circulatory cells, two upstream and two downstream for the wire. The cross-flow weakens the intensity of EHD flow. With the increase of the inlet velocity, the cross-flow causes the two circulatory cells near the corona wire to merge into one circulatory cell. For particles, a Monte-Carlo simulation is applied to describe *in situ* particle charging and tracing. In the current model we consider the effect of the fluid turbulence on the particle movement; give the particle charging history; and clarify the magnitude of the electric field force, the drag force, the gravitational force, the buoyancy force, the virtual mass force, the Basset history force, the Saffman lift force and the pressure gradient force on particle motion.

As discussed in Chapter 4, radio-frequency (RF) circuits have been widely designed and fabricated in CMOS processes due to the advantages of high integration and low cost for mass production. Electrostatic discharge (ESD), which has become one of the most important reliability issues in IC products, must be taken into consideration during the design phase of all ICs, including the RF front-end circuits. Without ESD protection circuits at all I/O pads, the RF performance of a wireless transceiver can be easily damaged by ESD stresses, because RF front-end circuits are always fabricated in advanced CMOS processes. Usually the I/O pads are connected to the gate terminal of MOS transistor or silicided drain/source terminal, which leads to a very low ESD robustness if no ESD protection design is applied to the I/O pad. Once the RF front-end circuit is damaged by ESD, it can not be recovered and the RF functionality is lost. Therefore, on-chip ESD protection circuits must be provided for all I/O pads in RF ICs.

Chapter 5 discusses powder coating, which is an important process in the food industry, especially for snack foods. Powder coating creates variety in food, producing different flavors and appearance. Electrostatic coating has been adopted in order to provide better efficiency and lower the dust produced during coating. Electrostatic coating is usually done with a corona system to charge the powder. There are two systems used to coat the food: a tumble drum coating system and a conveyor belt coating system. The tumble drum coating system is used to coat all sides of the food product. The conveyor belt coating system only coats one side of the product but most consumers do not notice this. The efficiency of electrostatic coating is affected by characteristics of the powder, including particle size, density, resistivity, and flowability. Surface characteristics of the food to be coated are also important.

These factors affect the transfer efficiency, adhesion, dust, evenness, and functionality of the powder on the targets. An understanding of these factors can be used to predict the coating performance in food production and help the processor choose the best system for coating food products.

Chapter 6 presents the evaluation of capacitance of arbitrary-shaped conducting bodies using Method of Moments. The conducting surfaces are modeled by planar rectangular subdomains in which the charge density is assumed to be constant over each subsection. The exact formulation for the matrix element is evaluated for rectangular subsection. The capacitances of different conducting structures, e.g. square, circular, triangular, wedge-shaped plate and also multiconducting bodies e.g. transmission lines with square, circular cross section are evaluated here. In the next part of the chapter, work is extended for the evaluation of static charge distribution and capacitance of conducting bodies from the measured electric field components due the same. The computed results show good agreement with other available results in literature.

The spatial distributions of electric field and charge are the most frequent subjects of classical electrostatic problems. In Chapter 7, the spatial spectrum of the charge distribution on planar systems of strips is studied. Due to the charge singularities at the strip edges and strong dependence of the spectrum on the distribution details over the entire system, the direct application of the Fourier transformation to the charge spatial distribution yields results with unsatisfactory accuracy. Here a method of direct evaluation of the charge spatial spectrum is proposed and discussed; the spatial distribution is obtained from it by the inverse Fourier transformation for certain auxiliary purposes and final verification of numerical results. The solution is constructed as a linear combination of the template functions, evaluated in spectral domain, satisfying the electric boundary conditions on the strips, and having known spatial spectrum. The same functions are applied in the solution of the complementary problem of strips in external electric field. The flexibility of the method is illustrated in two examples. Namely, the quasi-periodic system of strips with periodicity broken by inclusion of one narrower strip is considered first. Also, the problem of acoustic beam forming analysis is treated by the presented method.

Electroporation also called *Electropermeabilization*, is the use of high magnitude electric field pulses to alter the permeability of a cell membrane. This change in permeability is achieved by using an electric field pulse to induce nanoscopic 'pores' in the cell membrane. These pores are commonly called 'electropores,' which is why the process is commonly referred to as *electroporation*. Many biotechnological applications and research require transport of macromolecules such as genes, antibodies, and chemical drugs, into a host cell. For any particular application, choosing a given transfer process is based on its efficacy, ease of use and side effects. A characteristic shared by most of the chemical and biological techniques is that they are usually cell-type dependent and have relatively poor efficiencies.

Therefore, methods which are both versatile and efficient are being searched for and investigated. Electroporation, first reported in 1982 (Neumann *et al.*, 1982), is one of the methods reported to be effective for such delivery. Since its inception, this method has been a valuable tool for *in vitro* delivery of small and large molecules into a large variety of cells. During this time, electroporation has been performed on living plants, animals, and humans (*in vivo* electroporation), with an increasing focus on therapeutic uses (Dev *et al.*, 2000; Smith and Nordstrom, 2000; Muramatsu *et al.*, 1998).

Chapter 8 covers important aspects of electroporation including induced transmembrane potential, formation of pores, relation between pore radii and pore energy, pore density and current through electropores. This knowledge is useful for simulating electroporation results which can be helpful for making informed decisions about electroporation system parameters.

In the latest research developments, a great interest in the scientific community is dedicated also on study of the atmospheric state in the lower part of the troposphere. This part of the atmosphere is our living environment, and so it is the source of our breathing air. The atmospheric studies are a multidisciplinary science. It concerns on the measurement of both, the physical and chemical atmospheric parameters. In Chapter 9, the author is concentrated on the continuous monitoring of the physical atmospheric parameters, especially electrical parameters of lower part of the troposphere. The principal electrical parameters of the atmosphere are atmospheric ion concentration, density current, atmospheric electric fields, aerosol concentration, etc.

Atmospheric ion and aerosol concentration are the principal electrical parameters monitored in my measurement campaigns. Atmospheric ions belong on the small air ion group. In the case of aerosol monitoring, there are done two types of measurements; aerosol number concentration, for the aerosol particles in the size interval (0.3-100μm), and aerosol mass concentration, for three aerosol groups PM1, PM2.5 and PM10.

The electrical state of the atmosphere is strongly connected with the area category. So, all the monitoring process is carried out in four main areas; urban, rural, seashore and mountain.

Based on the measurement results, the author studied the daily and annual variation of the atmospheric ion and aerosol particle concentration.

During the measurements are recorded also the principal meteorological parameters. These parameters are air temperature, atmospheric pressure, relative humidity and wind speed. There are carried out the correlations among atmospheric and aerosol concentration and the above mentioned meteorological parameters.

Analyzing the variation of the concentrations, the author determined the recombination and the attachment coefficients, so giving a clear picture of the electrostatic interaction among atmospheric ions and aerosol particles in certain areas.

The concentrations of both atmospheric ions and aerosol particles are also altitude dependent, in the exponentially decay form. The measurements on the different altitudes enable to determine the scale height of their concentrations and the analytical functions.

It is important to mention that the author's research activities on the atmospheric electricity are developed mainly in the fair weather conditions of the atmosphere.

CONTENTS

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Chapter 1

ASYMMETRIC ELECTROSTATIC FORCES AND A NEW ELECTROSTATIC GENERATOR

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Abstract

It is well known that there are three kinds of electrostatic force: gradient force, image force, and Coulomb force. A gradient force acts on a non-charged body that is placed in a convergent electric field. An image force acts on a charged body placed near a conductive plate. A Coulomb force acts on a charged body placed in an electric field. As for the shape of these bodies, only symmetric forms have been treated in the past. The representative example for all three force types is a sphere. Forty years ago, only the potential of a spherical body could be calculated. In contrast, today, we can calculate the potential of any shape by computer simulation.

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present a concrete design and a prospective performance of this electrostatic generator. It is expected that the earth environmental problem and the energy crisis can be simultaneously solved with this new electrostatic generator.

Finally, I will introduce an unusual phenomenon in which the direction of the ACF does not change, even if the electric field surrounding the asymmetric charged conductor is reversed. This unusual phenomenon is made possible by appropriately designing the shape of the conductor; thus, it resembles the phenomenon in which a yacht can advance diagonally in a head wind.

1. Asymmetric Force (AF)

1.1. Purpose

In a convergent electric field, all bodies are forced to move in the convergent direction by an electrostatic force. This is the gradient force. The other two electrostatic forces (the image force and the Coulomb force) act only on charged bodies, but the gradient force can also act on neutral objects. This is a very useful characteristic. However, a gradient field is not particularly useful. If a non-charged material could be forced to move in a parallel electric field by electrostatic force, this would be a very useful phenomenon.

Thus, the following hypothesis is proposed.

Hypothesis: When a convergent field is changed to a parallel field, if the shape of a non-charged conductor is changed precisely in proportion to the change of the field, the same electrostatic force will act on the altered non-charged conductor.

The above phenomena are proposed to be mathematically equivalent. As a note, in this paper, only the electrostatic force that acts on a conductive body was simulated for simplification.

Therefore, it is a main purpose of this chapter to prove this hypothesis. In addition, finding the optimal shape for this force and confirming this force experimentally are the second and third purposes of this chapter.

1.2. Simulation Methods and Results

If these two forces that act on the original conductor in a convergent field and the altered conductor in parallel field could be calculated analytically, this task would be easy. However, there is no formula that can be used to calculate these forces for all shapes. There exists only an approximate formula for small spheres in a convergent field [1]. This situation is shown schematically in Figure 1. The following is the approximate formula for a small conductive sphere.

$$Fg = 2\pi r^3 \varepsilon_0 \nabla E_0^{\ 2} \tag{1}$$

where r: Radius of the sphere.

E_0: Intensity of the convergent field around the sphere

ε_0: Vacuum permittivity

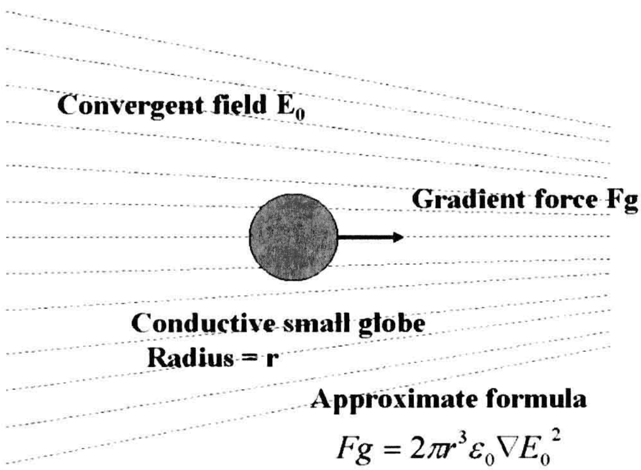

Figure 1. Schematic view of the gradient force and an approximate formula for a sphere.

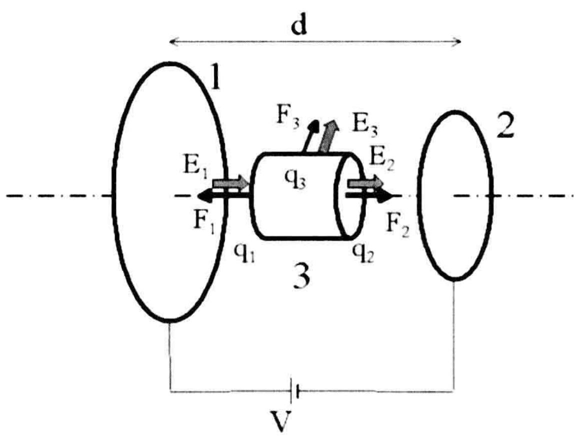

Figure 2. Schematic layout for simulating the electrostatic force acting on a cylinder in a convergent field.

Therefore, I used a simulation method to calculate these forces. It would be ideal to simulate these forces in three dimensions. However, the simulation program, which was written by the author, is only a bi-dimensional program, employing an axi-symmetric finite difference method. Fortunately, this simulation program can treat an axi-symmetric body. Hence, a cylinder-shaped conductor was selected in place of the conductive small sphere; this cylinder-shaped conductor is hereafter referred to as a cylinder.

Figure 2 shows a cylinder placed in the convergent field. This field is formed by two disc electrodes that have different diameters.

Figure 2 shows a schematic layout for the simulation. A large circle electrode (**1**), a small circle electrode (2), and a cylinder (3) were aligned along the z axis (the dotted line in Figure 2). The radii of the large electrode, the small electrode, and the cylinder were 250 μm, 100 μm, and 100 μm, respectively. The distance between the large and small electrodes was 600 μm, and the width of the cylinder was 300 μm. A positive voltage of 600 V was applied to the large circle electrode in order to generate a convergent electric field between it and the grounded small circle electrode. The cylinder was electrically floated.

E_1, E_2, and E_3 are the electric field intensities on the left surface, the right surface, and the circumference surface of the cylinder, respectively, while q_1, q_2, and q_3 are the charge quantities of the left surface, the right surface, and the circumference surface of the cylinder, respectively. F_1, F_2, and F_3 are the electrostatic forces acting on the left surface, the right surface, and the circumference surface of the cylinder, respectively.

The total electrostatic force Fe that acts on the conductor was calculated using the following formula, (2)

$$Fe=F_1+F_2 \tag{2}$$

F_3, which acts on the circumference surface of the cylinder, was not included in formula (2) because it cancels out at an interval of 180 degrees and ultimately becomes zero.

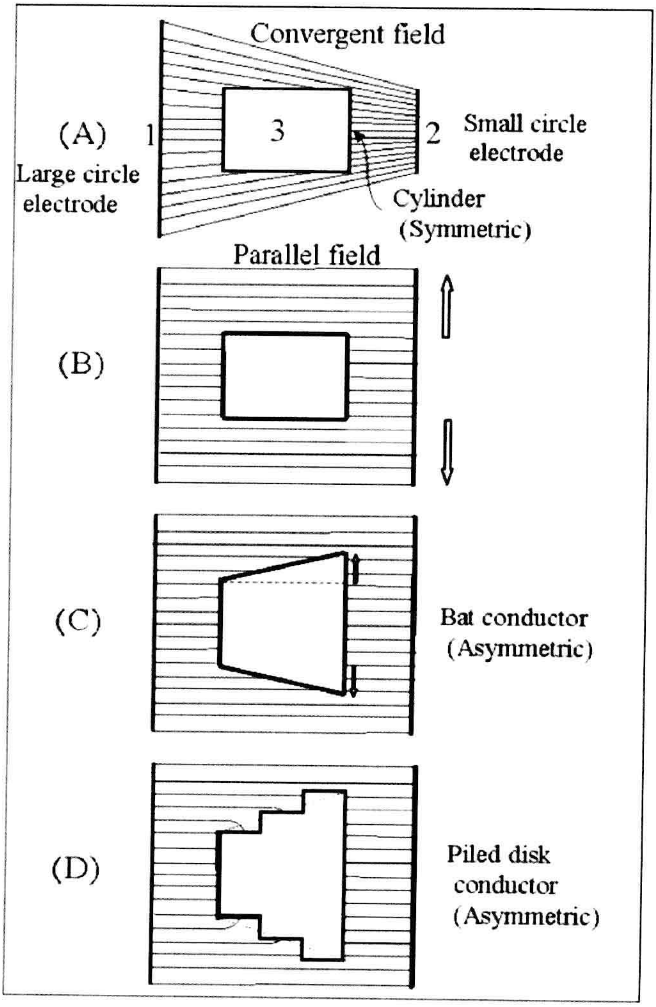

Figure 3. Schematic diagram of electric field patterns and conductor shapes. (A) A convergent field and a cylinder. (B) A parallel field and a cylinder. (C) A parallel field and a baseball-bat-shaped conductor. (D) A parallel field and a piled disk conductor.

The details of this simulation are explained in Appendix 1.

The gradient force that acts on a non-charged cylinder in a convergent field (see Figure 3 (A)) was simulated using an axi-symmetric finite difference method.

Then, the electrostatic force that acts on a cylinder in a parallel field (see Figure 3 (B)) and the force that acts on a piled disk conductor in a parallel field (see Figure 3 (D)) were simulated.

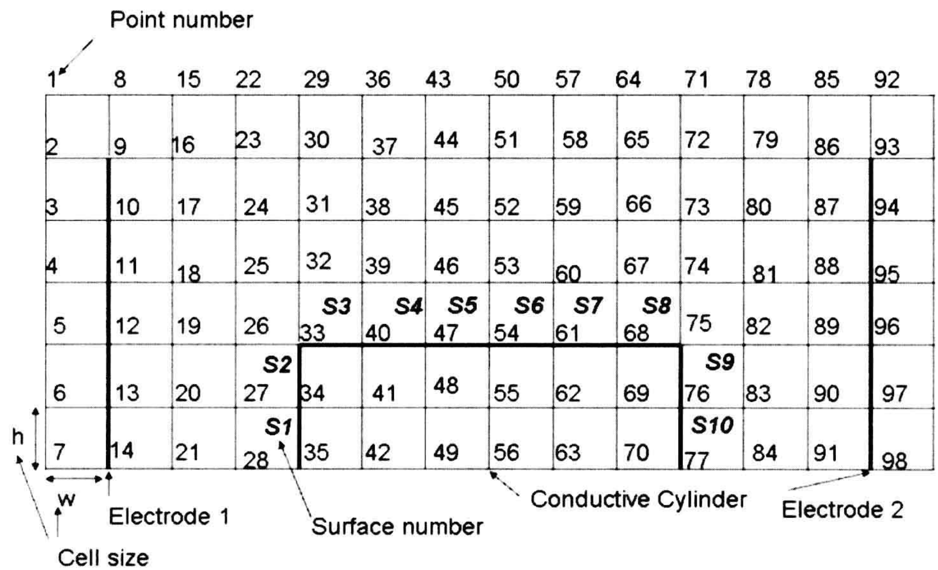

Figure 4. A design of cells (mesh) for simulating the electrostatic force that acts on a non-charged cylinder in a parallel electric field.

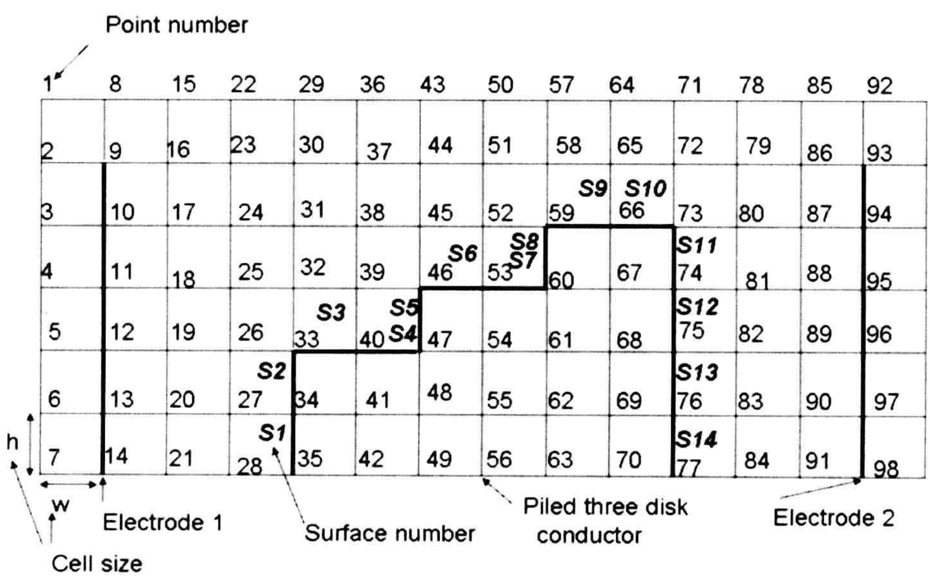

Figure 5. A design of cells (mesh) for simulating the electrostatic force that acts on a non-charged piled three-disk conductor in a parallel electric field.