

Polarisation Behaviour of Charged Particles in Uniform and Non-Uniform Static Electric Fields

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Citation: Chaudhary, J. & Saini, G. (2026). Polarisation Behaviour of Charged Particles in Uniform and Non-Uniform Static Electric Fields. International Journal of Education, Modern Management, Applied Science & Social Science, 08(03(III)), 27–32. [https://doi.org/10.62823/IJEMMASSS/8.3\(III\).9476](https://doi.org/10.62823/IJEMMASSS/8.3(III).9476)

ABSTRACT

The interaction of charged and polarizable particles with static electric fields is a fundamental problem in classical electrostatics and has direct relevance to electrostatic precipitation, particle separation, colloidal processing, microfluidics, aerosol control, and biomedical manipulation. This paper examines the polarisation behaviour of charged particles in uniform and non-uniform static electric fields by distinguishing the force associated with net electrical charge from the force created by field-induced polarisation. A particle carrying net charge q in an electric field $\vec{E}$ experiences the Coulomb force $q\vec{E}$. At the same time, the field may redistribute bound or mobile charges within the particle and its interface, creating an induced dipole moment. In an ideal uniform field, the forces acting on the two poles of an induced dipole balance, so the dipole alone produces no net translational force, although torque, orientation, interfacial charge redistribution, and deformation may occur. In a non-uniform field, the two poles experience different field strengths, generating a net gradient-dependent polarisation force. This effect is the basis of dielectrophoresis. The paper develops the classical equations governing these processes, compares particle response in the two field configurations, and discusses the effects of particle size, charge, permittivity, conductivity, shape, medium viscosity, and electric-field gradient. The analysis shows that practical particle motion frequently results from the combined action of Coulombic, polarisation, hydrodynamic, and thermal forces. Understanding these mechanisms is essential for predicting and controlling particle transport, trapping, separation, and assembly in electrostatic systems.

Keywords: Polarisation, Charged Particles, Static Electric Field, Uniform Electric Field, Non-Uniform Electric Field, Induced Dipole, Dielectrophoresis, Electrostatic Force.

Introduction

The motion of matter in an electric field is usually introduced through the elementary electrostatic relation between force, charge, and field. For an isolated point charge, this treatment is sufficient. Real particles, however, have finite dimensions, internal electrical structure, interfaces, and material-dependent dielectric properties. Consequently, their behaviour in an applied electric field can involve both translation of net charge and redistribution of charge within the particle. This redistribution is described as polarisation and may generate an induced electric dipole. The resulting electromechanical response depends not only on the amount and sign of the particle's net charge but also on the spatial distribution of the applied field and on the electrical contrast between the particle and its surrounding medium [1-4].

Polarisation can originate through several mechanisms. Electronic polarisation results from a small displacement of an electron cloud relative to the atomic nucleus. Ionic polarisation occurs when

positive and negative ions are displaced relative to one another. Polar molecules may undergo orientational polarisation, while heterogeneous particles suspended in fluids may develop pronounced interfacial or Maxwell-Wagner polarisation because charges accumulate where materials of different permittivity and conductivity meet [3,5]. At small length scales, surface conductivity, the electrical double layer, and charge relaxation can further modify the effective response of a particle. Thus, a particle may be electrically neutral overall and still experience a force in a suitably non-uniform field, or it may be charged and simultaneously exhibit an induced-dipole response.

The distinction between uniform and non-uniform electric fields is central to particle electromechanics. In a uniform field, the electric-field vector is approximately constant over the dimensions of the particle. A net charged particle therefore experiences a direct Coulomb force, whereas the opposite poles of an ideal induced dipole experience equal and opposite forces. In a non-uniform field, the field varies from one side of the particle to the other. The unequal forces on the induced poles produce a net translational force that depends on the field gradient. Pohl termed this gradient-driven motion dielectrophoresis, and later theoretical treatments established it as a major method for manipulating dielectric particles [1,2,6].

Theoretical Basis of Particle Polarisation

Consider a spherical particle of radius a and dielectric permittivity ϵ_p immersed in a medium of permittivity ϵ_m . When a static electric field is applied, the positive and negative charge distributions within the particle respond to the field. For a linear, isotropic particle whose response is not saturated, the induced dipole moment $\vec{p}$ can be written in terms of the local field $\vec{E}$ and an effective polarizability α [2,3]. Throughout the equations below, an over-arrow denotes a vector quantity.

$$\vec{p} = \alpha \vec{E} \quad (1)$$

For an ideal homogeneous dielectric sphere in an infinite dielectric medium, the static dipolar polarizability is given by the classical Clausius-Mossotti form:

$$\alpha = 4\pi\epsilon_m a^3 [(\epsilon_p - \epsilon_m)/(\epsilon_p + 2\epsilon_m)] \quad (2)$$

The dimensionless factor $K = (\epsilon_p - \epsilon_m)/(\epsilon_p + 2\epsilon_m)$ describes the dielectric contrast between the particle and its environment. When ϵ_p is greater than ϵ_m , K is positive and the particle is more readily polarized than the surrounding medium. If ϵ_p is less than ϵ_m , K is negative in the ideal dielectric model. The induced dipole moment scales with particle volume, explaining why polarisation forces become rapidly weaker as particle radius decreases [2,7].

Net particle charge and induced polarisation should not be treated as identical quantities. Net charge represents an excess or deficiency of charge carried by the particle as a whole. Polarisation instead represents a spatial separation of positive and negative charge while often preserving the total charge. A charged particle can therefore experience both a monopole force associated with q and a dipolar force associated with $\vec{p}$. This superposition provides a useful first approximation for analysing charged, polarizable particles in external fields.

Behaviour in a Uniform Static Electric Field

In an ideal uniform static electric field, $\vec{E}$ has essentially the same magnitude and direction throughout the region occupied by the particle. A particle with net charge q experiences the direct electrostatic or Coulomb force

$$\vec{F}_c = q\vec{E} \quad (3)$$

The direction of this force depends on the sign of q . A positively charged particle moves in the direction of the field, while a negatively charged particle moves in the opposite direction. In vacuum, the resulting acceleration is $\vec{a} = q\vec{E}/m$. In a liquid or gas, however, viscous drag becomes important and a steady migration velocity may develop rather than continued acceleration. For a slowly moving spherical particle in a Newtonian fluid, the Stokes drag force vector is approximately $-6\pi\eta a\vec{v}$, where η is the dynamic viscosity and $\vec{v}$ is the particle velocity [8].

Polarisation still takes place in a uniform field. The external field displaces charge and produces an induced dipole, but the ideal dipole does not experience a net translational force. The positive effective pole is pulled in the field direction and the negative effective pole is pulled in the opposite direction with equal magnitude. Their contributions therefore cancel. Mathematically, the translational dipole force contains a spatial derivative of the field; for an ideal uniform field, the spatial gradient of $\vec{E}$ vanishes, so the gradient-dependent contribution is zero [1,2].

A uniform field can nevertheless produce rotational effects. A permanent dipole or an anisotropic induced dipole experiences an electrical torque

$$\vec{\tau} = \vec{p} \times \vec{E} \quad (4)$$

The torque tends to align the dipole with the field. This phenomenon is important for elongated particles, fibres, rods, nonspherical colloids, and biological structures whose polarizability differs along different axes. Even a spherical particle may exhibit interfacial charge redistribution, but its rotational behaviour is more symmetric. Uniform fields can also contribute to deformation of liquid droplets or soft particles because electrical normal and tangential stresses act at the interface [9].

Behaviour in a Non-Uniform Static Electric Field

When the applied static field varies with position, the two sides of an induced dipole are subjected to different field strengths. The force on the pole located in the stronger field is not exactly balanced by the force on the opposite pole. A net translational polarisation force is therefore generated. For a sufficiently small dipole in a slowly varying electrostatic field, the force may be written as

$$\vec{F}_p = (\vec{p} \cdot \nabla) \vec{E} \quad (5)$$

If the induced dipole is proportional to the field, $\vec{p} = \alpha \vec{E}$, and the particle is isotropic, the force can be expressed in a form proportional to the gradient of the squared field magnitude:

$$\vec{F}_p \approx \frac{1}{2} \alpha \nabla E^2 \quad (6)$$

For an ideal spherical dielectric particle, substitution of the Clausius-Mossotti polarizability produces the familiar dielectrophoretic dependence

$$\vec{F}_{DEP} = 2\pi \epsilon_m a^3 K \nabla E^2 \quad (7)$$

The exact prefactor depends on the field convention and model assumptions, but the physical scaling is unambiguous: the dielectrophoretic force increases with particle volume, dielectric contrast, and the gradient of E^2 [1,2,6]. Electrode tips, narrow gaps, insulating constrictions, and patterned microelectrodes are therefore used to create strong field gradients.

For a particle that also carries a net charge, the electrical force can be approximated as the sum of the monopole and dipole contributions:

$$\vec{F}_{electric} \approx q\vec{E} + (\vec{p} \cdot \nabla) \vec{E} \quad (8)$$

This expression illustrates why charged particles in non-uniform fields can behave differently from ideal point charges. The Coulomb term depends linearly on q and E , whereas the polarisation term depends on the particle's electrical properties, size, and the spatial derivative of the field. Depending on direction and magnitude, the two terms may reinforce or oppose one another. In a fluid, both must also compete with hydrodynamic drag, gravity, Brownian diffusion, and possibly electroosmotic flow.

Positive and Negative Dielectrophoretic Response

The direction of the gradient-driven force is controlled by the effective polarizability of the particle relative to the surrounding medium. In the simplest static dielectric model, a positive Clausius-Mossotti factor causes the particle to move toward regions of larger E^2 . This is commonly described as positive dielectrophoresis. A negative factor produces motion toward weaker-field regions and is termed negative dielectrophoresis [2,6,10].

For strictly direct-current or very-low-frequency conditions, however, the final response of a real suspended particle may depend strongly on electrical conductivity and interfacial charge relaxation rather than on permittivity alone. When the particle and medium have different conductivities, charges accumulate at the interface and modify the induced dipole. At micro- and nanoscale dimensions, electrical double layers and surface conduction may become comparable to the bulk response [6,11]. Consequently, simple dielectric equations are most reliable as conceptual models, while accurate quantitative predictions may require electrokinetic and interfacial models appropriate to the particle, medium, and electrode configuration.

Comparison of Particle Behaviour in Uniform and Non-Uniform Fields

The essential differences between the two field configurations are summarized in Table 1. The comparison shows that the spatial gradient of the field introduces an additional mechanism for selective particle manipulation that is absent from the ideal uniform-field case.

Table 1: Comparison of Charged-Particle Behaviour in Uniform and Non-Uniform Static Electric Fields

Characteristic	Uniform Static Field	Non-uniform Static Field
Field magnitude	Approximately constant over the particle	Varies spatially over the particle
Force on net charge	$q\vec{E}$	$q\vec{E}$, with local magnitude varying by position
Induced dipole formation	Occurs	Occurs
Ideal net force on induced dipole	Approximately zero	Non-zero when a field gradient exists
Rotational torque	Possible	Possible
Dependence on $ \nabla \vec{E} ^2 $	Negligible for ideal uniform field	Fundamental to dielectrophoretic force
Particle trapping by polarisation	Not possible in an ideal unbounded uniform field	Readily possible near strong field gradients
Primary selectivity	Mainly sign and magnitude of net charge	Charge plus size and electrical polarizability

Factors Controlling Polarisation and Motion

Particle size is one of the strongest parameters governing polarisation force. Equation (7) shows an approximate a^3 dependence for an ideal sphere. Doubling the particle radius can therefore greatly increase the dielectrophoretic force. At the same time, Stokes drag increases approximately with a , while Brownian diffusion becomes relatively more significant as particle size decreases. These competing scalings explain why nanoscale manipulation often requires very large field gradients and careful control of thermal and surface effects [6,8].

Net charge determines the magnitude of the Coulomb term. Two particles having the same size and dielectric properties but different charges may migrate at different velocities in a uniform field. In contrast, two particles with similar net charges may respond differently in a non-uniform field if their permittivities, conductivities, sizes, or shapes differ. This distinction is one reason dielectrophoretic methods can provide selectivity that conventional electrophoretic motion cannot provide by charge alone.

The surrounding medium is equally important. Permittivity affects the electric energy stored around the particle, conductivity controls charge relaxation, and viscosity determines hydrodynamic resistance. In electrolytes, ionic strength influences the electrical double layer and electroosmotic effects. Temperature can change viscosity and conductivity and may also cause electrothermal flow when high fields produce Joule heating. Although these secondary processes lie beyond ideal electrostatics, they can dominate practical microfluidic experiments if not controlled [13].

Applications of Controlled Particle Polarisation

Electrostatic precipitation is one of the most established applications of electrical particle control. Aerosol particles are electrically charged and driven toward collecting electrodes. The principal collection mechanism is Coulombic, but local field gradients and particle polarisation can alter trajectories, especially near electrodes and neighbouring particles. Similar principles are relevant to powder handling, contamination control, and electrophotographic technologies.

Microfluidics has become a major application area for non-uniform-field polarisation. Patterned electrodes or insulating structures create strong gradients over micrometre-scale distances, allowing cells, polymer beads, droplets, and other particles to be trapped, focused, deflected, or concentrated. Because the response depends on electrical polarizability, dielectrophoresis can discriminate between particles that have similar sizes but different membrane, cytoplasmic, surface, or material properties [10,16].

Limitations of the Classical Electrostatic Model

The dipole model provides a clear physical description but relies on simplifying assumptions. It generally assumes that the particle is much smaller than the length scale over which the external field varies, that the particle is isolated, and that its response is linear. It also neglects higher-order multipoles, strong surface charge, nonlinear dielectric behaviour, close proximity to boundaries, and detailed electrohydrodynamic coupling. These assumptions can fail for large particles near sharp electrode features or for densely packed suspensions [2,17].

Discussion

The analysis demonstrates that charged-particle behaviour cannot be completely described by qE^+ whenever the particle has finite size and significant polarizability. The Coulomb force is determined by net charge, whereas the induced-dipole response is determined by redistribution of charge and the spatial variation of the field. In a perfectly uniform field, this redistribution does not by itself generate a net translational force on an ideal dipole. It can, however, produce torque and changes in interfacial charge distribution. A non-uniform field removes the force symmetry across the dipole and thereby converts polarisation into translational motion.

This distinction has important consequences for particle control. Uniform fields are effective for transporting charged particles according to charge polarity and magnitude. Non-uniform fields introduce an additional degree of selectivity based on particle size and electrical properties. A properly designed gradient can therefore trap or separate particles even when their net charges are weak or similar. Conversely, for strongly charged particles the Coulomb force can dominate the polarisation term, and a quantitative treatment must evaluate both contributions rather than assuming a purely dielectrophoretic mechanism.

Conclusion

Polarisation is a fundamental component of the response of finite-sized charged particles to static electric fields. An applied field can redistribute charge within a particle and at its interface, thereby creating an induced dipole in addition to any net charge already carried by the particle. In a uniform static electric field, the direct Coulomb force qE^+ produces translation of a net charged particle, whereas the forces on the opposite poles of an ideal induced dipole cancel. Polarisation may still produce torque, alignment, interfacial charge redistribution, and deformation. In a non-uniform field, the cancellation is incomplete because the two poles experience different field strengths. The resulting force is proportional to the particle polarizability and to the spatial gradient of the field energy, giving rise to dielectrophoresis. For charged and polarizable particles, Coulombic and gradient-dependent forces can act simultaneously and may reinforce or oppose one another. Particle radius, net charge, permittivity, conductivity, shape, concentration, medium viscosity, surface properties, and field geometry all influence the observed behaviour. These principles explain why non-uniform electric fields provide powerful control over particle trapping, sorting, assembly, and transport. They also show why realistic predictions require attention to hydrodynamic drag, Brownian motion, interfaces, boundaries, and interparticle interactions. A clear distinction between net-charge effects and induced-polarisation effects therefore provides the essential theoretical basis for designing and interpreting modern electrostatic particle-manipulation systems.

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