

## Electrophoretic mobility of charged porous shells or microcapsules and electric conductivity of their dilute suspensions



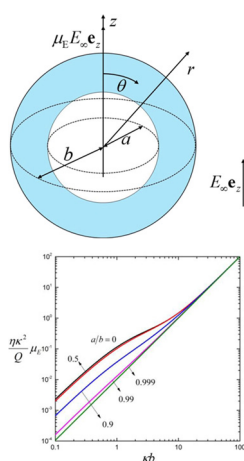
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### HIGHLIGHTS

- The electrophoretic mobility of a charged porous shell is analytically obtained.
- The electric conductivity of a suspension of charged porous shells is analytically obtained.
- The mobility of the shell and conductivity of the suspension increase with the shell thickness.
- The effect of shell thickness on the mobility of a shell with low permeability is significant.
- The effect of shell thickness on the mobility of a shell with thick double layer is significant.

### GRAPHICAL ABSTRACT



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### ABSTRACT

An analysis is presented for the electrophoresis and electric conduction in a dilute suspension of charged spherical porous shells or permeable microcapsules with electric double layers of arbitrary thickness in an electrolyte solution. With the assumption that the system is slightly perturbed from equilibrium, the linearized electrokinetic equations governing the ionic electrochemical potential energy and fluid velocity distributions are solved as series expansions in the small fixed charge density of the porous shells. Explicit formulas for the electrophoretic mobility of the porous shells and effective electric conductivity of the suspension are derived. Both the electrophoretic mobility and the effective conductivity decrease monotonically with a decrease in the relative thickness of the porous shells, but these decreases are not conspicuous until the porous shells are quite thin. When the fluid permeability of the porous shells is smaller or the electric double layers are thicker, the effect of this relative thickness on the electrophoretic mobility and effective conductivity becomes more significant. In the limiting case of zero inner radius of the porous shells, our formulas reduce to the corresponding results obtained for the electrophoresis and electric conduction in a suspension of charged porous spheres.

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## 1. Introduction

When charged colloidal particles suspended in an electrolyte solution are subject to an external electric field, both the particles and the small ionic species are driven to migrate. Consequently, the fluid is dragged to flow by the electrophoresis of the particles and the motion of the ions, attended by an electric current. In the past, many expressions for the electrophoretic mobility and effective electric conductivity have been obtained for suspensions of hard (impermeable to the electrolyte solution) spherical particles [1–8].

Many colloidal particles, such as macromolecules and flocs of nanoparticles, are porous and permeable to the electrolyte solution. Analytically solving the electrokinetic governing equations (including a modified Stokes/Brinkman equation) for a dilute suspension of porous spheres with uniform densities of hydrodynamic frictional segments and fixed charges surrounded by electric double layers of arbitrary thickness under an applied electric field, Hermans and Fujita [9] and Liu and Keh [10] derived explicit formulas for the electrophoretic mobility of the porous spheres and effective electric conductivity of the suspension, respectively. Recently, these analyses have been extended to concentrated suspensions of porous spheres [11,12]. Some analytical expressions for the electrophoretic mobility and effective conductivity of suspensions of soft spheres (each is a hard spherical core covered with a porous surface layer of uniform thickness) have also been obtained [13–16].

In addition to the representation of a macromolecule, and a floc of nanoparticles, a porous shell of uniform thickness [17–19] can be used to model a microcapsule, which is a fluid drop bounded by a permeable membrane, and the electrokinetic behavior of suspensions of charged microcapsules in an applied electric field is of interest [20]. In this paper, we consider the electrophoresis and electric conduction in a dilute suspension of charged porous spherical shells with arbitrary double layers. The ionic electrochemical potential energy and fluid velocity distributions are determined as series expansions in the small fixed charge density of the porous shells by solving the linearized electrokinetic governing equations subject to relevant boundary conditions. Explicit formulas for the electrophoretic mobility of the porous shells and effective electric conductivity of the suspension will be obtained as functions of the electrokinetic radius, normalized fluid permeability, and relative thickness of the porous shells.

## 2. Electrokinetic equations

In this section, we consider a charged porous spherical shell of inner radius  $a$  and outer radius  $b$  in a liquid solution containing  $M$  ionic species (which is permeable through the porous shell) subjected to a constant applied electric field  $E_\infty \mathbf{e}_z$  at the steady state, and the velocity of the porous shell due to electrophoresis is  $\mu_E E_\infty \mathbf{e}_z$ , where  $\mathbf{e}_z$  is a unit vector in the  $z$  direction and  $\mu_E$  is the electrophoretic mobility of the porous shell to be determined. As shown in Fig. 1, the origin of the spherical coordinates  $(r, \theta, \phi)$  is set at the center of the porous shell and the problem is axially symmetric about the  $z$  axis.

### 2.1. Governing equations

It is assumed that the applied electric field is not strong and the system is only slightly distorted from equilibrium. Thus, the concentration (number density) distribution  $n_m(r, \theta)$  of the ionic species  $m$  and the electric potential distribution  $\psi(r, \theta)$  can be expressed as

$$n_m = n_m^{(\text{eq})} + \delta n_m, \quad (1a)$$

$$\psi = \psi^{(\text{eq})} + \delta \psi, \quad (1b)$$

where  $n_m^{(\text{eq})}(r)$  and  $\psi^{(\text{eq})}(r)$  are the equilibrium concentration of the ionic species  $m$  and electric potential, respectively, and  $\delta n_m(r, \theta)$  and  $\delta \psi(r, \theta)$  are the small perturbations to the equilibrium state (in which no electric field is imposed). The equilibrium concentration of each ionic species is related to the equilibrium electric potential by the Boltzmann distribution.

The small perturbed quantities  $\delta n_m$  and  $\delta \psi$  together with the velocity distribution  $\mathbf{u}(r, \theta)$  of the incompressible Newtonian fluid are governed by the following differential equations linearized from the continuity equation of the ionic species  $m$  and modified Stokes/Brinkman equation, respectively [10]:

$$\nabla^2 \delta \mu_m = \frac{z_m e}{kT} [\nabla \delta \mu_m \cdot \nabla \psi^{(\text{eq})} - \frac{kT}{D_m} \mathbf{u} \cdot \nabla \psi^{(\text{eq})}], \quad m = 1, 2, \dots, M, \quad (2)$$

$$\nabla^2 \nabla \times \mathbf{u} - \lambda^2 h(r) \nabla \times \mathbf{u} = \frac{e}{\eta kT} \sum_{m=1}^M z_m n_m^\infty \exp\left[-\frac{z_m e}{kT} \psi^{(\text{eq})}\right] \nabla \delta \mu_m \times \nabla \psi^{(\text{eq})}, \quad (3)$$

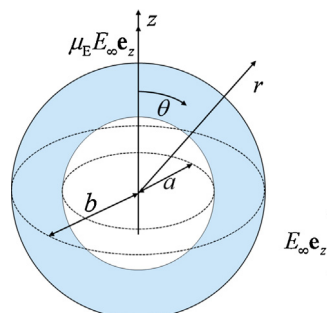


Fig. 1. Geometrical sketch for the electrophoresis of a charged porous spherical shell.

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