Separation and Purification Technology 156 (2015) 84–91

Contents lists available at ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Effect of flow path structure on solid/liquid separation under electric field

T. Tanaka [a], H. Kato [a], K. Fujihara [a], M.S. Jami [b], M. Iwata [a,*]

[a] Department of Chemical Engineering, Graduate School of Engineering, Osaka Prefecture University, Sakai, Osaka, Japan
[b] Department of Biotechnology Engineering, Faculty of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 10 November 2014
Received in revised form 21 June 2015
Accepted 24 June 2015
Available online 29 June 2015

Keywords:
Electroosmosis
Colloid
Dewatering
Sedimentation
Permeation

ABSTRACT

Electroosmosis is especially effective in removing liquid from a highly compressible difficult-to-filter solid/liquid mixture. The extent of solid/liquid separation depends on the electroosmotic pressure gradient (E_{pg}) which is a combination of applied electric field, the surface charge density of solid particles and the flow path structure in the mixture. The larger the E_{pg} value, the higher the solid content of the treated mixture. A theoretical equation of E_{pg} for a capillary flow is derived from the Navier–Stokes equation, and its extensions to a flow through porous materials are examined by using experimental E_{pg} values from constant-current electroosmotic dewatering (EOD), electroosmotic permeation (EOP) and electro-forced sedimentation (EFS) tests. It has been clarified that the specific hydrodynamic resistance α has the most effect on the E_{pg} value. The larger the α value of the material, the larger its E_{pg} value. Modifications to the existing theories were suggested to understand the effect of solid/liquid mixture concentration on the separation under electric field more precisely.

1. Introduction

Electroosmosis is the motion of liquid induced by an applied electric field across a porous material, capillary tube, membrane, microchannel, or any other flow channel. Electroosmosis has been used for sludge dewatering since the early 1900s [1,2] and this engineering technique was named "electroosmotic dewatering (EOD)". EOD is especially effective in removing liquid from the sludge of colloidal particles for which conventional mechanical dewatering is not very successful; i.e. such sludge is usually highly compressible, and mechanical dewatering is impeded due to a very high hydrodynamic resistance of the sludge. On the other hand, the high surface charge density of colloidal particles leads to a high electroosmotic flow rate under an applied electric field.

In our previous papers [3,4], it has been shown that apparent velocity u through a solid/liquid mixture can be represented by the extended Darcy equation shown in Eq. (1), in which the driving forces of the liquid flow are electroosmotic pressure gradient E_{pg} and liquid pressure gradient $dp_L/d\omega$.

$$u = \frac{1}{\mu\alpha\rho_s}\left(E_{pg} + \frac{dp_L}{d\omega}\right) \tag{1}$$

where μ is the liquid viscosity, α the specific hydrodynamic resistance of the mixture, and ρ_s the true density of solid. ω denotes the net solid volume per unit cross-sectional area extending from the drainage surface up to an arbitrary position in the mixture. E_{pg} is expressed as a combination of applied electric field, the surface charge density of solid particle and the flow path structure in the mixture, as shown in the next section. E_{pg} is defined as a positive value irrespective of the current direction and the sign of the surface charge of particles, since it is a driving force of electroosmosis. Combining Eq. (1) with the force balance equation in the mixture yields

$$u = \frac{1}{\mu\alpha\rho_s}\left(E_{pg} - \frac{dp_s}{d\omega}\right) \tag{2}$$

where p_s is the solid compressive pressure. It has also been shown that the EOD process can be recognized as a kind of consolidation since it accompanies the increase of solid compressive pressure in the mixture during the operation; the progress of EOD is expressed by the average consolidation ratio as in mechanical expression. The consolidation ceases when electroosmotic flow in any layer of the mixture is offset by the pressure flow in the layer. In other words, $dp_s/d\omega = E_{pg}$ in any layer of the mixture at the end of EOD. Thus, the final p_s distribution depends upon the E_{pg} value; the larger the value of E_{pg}, the larger the value of p_s-distribution in the mixture. Therefore, the extent of dewatering depends upon the

* Corresponding author.
E-mail address: iwata@chemeng.osakafu-u.ac.jp (M. Iwata).

http://dx.doi.org/10.1016/j.seppur.2015.06.035
1383-5866/

electroosmotic pressure gradient E_{pg}. Although an understanding of E_{pg} is essential to develop EOD processes of various materials, little attention has been paid to this parameter.

In this study, a theoretical equation of E_{pg} for a capillary flow and its extensions for a flow in porous material are derived from the Navier–Stokes equation. These equations include an influence of the porosity and its related factors on electroosmotic flow through the solid/liquid mixture in consolidation region. Factors contributing to the driving force of the solid/liquid separation using electroosmosis are discussed by analyzing these equations.

2. Theory

2.1. Electroosmotic flow through a capillary

The electroosmotic flow induced in a capillary tube has been modeled in a variety of ways. Kobayashi et al. solved the Navier–Stokes equation, taking into account the applied electric field strength $\boldsymbol{E}_o$ and the electric field strength in the double layer $\boldsymbol{E}_i$ caused by the contact potential difference ψ [5]. The equation of motion is expressed by

$$\rho\frac{D\boldsymbol{v}}{D\theta} = -\nabla p_L + \mu\nabla^2\boldsymbol{v} + \rho\boldsymbol{g} + \rho_e(\boldsymbol{E}_o + \boldsymbol{E}_i) \tag{3}$$

where ρ is the density of the liquid, $\boldsymbol{v}$ the velocity vector, θ the time, $D/D\theta$ the substantial time derivative, $\boldsymbol{g}$ the gravitational acceleration vector, and ρ_e the volumetric charge density of the liquid. Gauss's theorem for the electric flux density is

$$div[D(\boldsymbol{E}_o + \boldsymbol{E}_i)] = \rho_e \tag{4}$$

where D denotes the dielectric constant of liquid. The local ion density n_i of species i in dilute solutions is assumed to be of the Boltzmann type

$$n_i = \bar{n}_i \exp\left(-\frac{e_c z_i \psi}{k_B T}\right) \tag{5}$$

where $\bar{n}_i$ is the mean ion density of species i, e_c the elementary electric charge, z_i the valency of species i, k_B the Boltzmann constant and T the absolute temperature [5]. Kobayashi et al. arrived at the following solutions for a vertical capillary, in the case where the ion species in the solution are counter ions and both valencies are equal [5].

$$\psi = \zeta\frac{I_0(\kappa r)}{I_0\{\kappa(R-\delta)\}} \tag{6}$$

$$v_z = \frac{D\zeta E_{oz}}{\mu}\left[\frac{I_0(\kappa r)}{I_0\{\kappa(R-\delta)\}} - 1\right] - \frac{(R-\delta)^2 - r^2}{4\mu}\frac{dP}{dz} \tag{7}$$

The average velocity $v_{z.av}$ in the capillary is expressed as follows:

$$v_{z\cdot av} = -\frac{D\zeta E_{oz}}{\mu}f - \frac{(R-\delta)^2}{8\mu}\frac{dP}{dz} \tag{8}$$

$$f = 1 - \frac{2}{\kappa(R-\delta)}\frac{I_1\{\kappa(R-\delta)\}}{I_0\{\kappa(R-\delta)\}} \tag{9}$$

where R is the capillary radius, δ the thickness from capillary wall to the slip plane, ζ the potential at the slip plane (i.e. ζ potential), and E_{oz} the electric field strength along the z-axis of the capillary. P is the modified pressure, defined by $dP/dz = dp_L/dz - \rho g$ where g is the gravitational acceleration. f in Eq. (8) is a factor denoted by Eq. (9), representing the effect of thickness of electrical double layer on the flow rate. κ in Eqs. (6), (7) and (9) is the Debye–Hückel parameter defined by

$$\kappa = \sqrt{\frac{2\bar{n}_i}{Dk_BT}}e_c z_i \tag{10}$$

In Eqs. (6), (7) and (9), $I_0(\kappa r)$ is the modified Bessel function of the first kind of order zero, while $I_1\{\kappa(R-\delta)\}$ is the modified Bessel function of the first kind of order one. The behavior of Eq. (9) is illustrated in Fig. 1. f approaches unity as the Debye–Hückel length $1/\kappa$ becomes small compared to the capillary radius R. On the other hand, f dropped to a low value under $(R-\delta)/(1/\kappa) < 10$. Rice and Whitehead [6] obtained similar equations with Eqs. (7) and (8), neglecting the gravity term.

2.2. Small pore and large pore approximation

When the capillary is so narrow that the liquid can be considered as homogeneously charged, Eq. (8) can be rewritten as [5]

$$v_{z\cdot av} = \frac{(R-\delta)^2}{8\mu}\left(\rho_e E_{oz} - \frac{dP}{dz}\right) \tag{11}$$

Schmid [7] proposed the same equation as the first term of Eq. (11).

When the capillary radius is very large compared to the thickness of the double layer, f denoted by Eq. (9) approaches unity, and Eq. (8) reduces to

$$v_{z\cdot av} = -\frac{D\zeta E_{oz}}{\mu} - \frac{(R-\delta)^2}{8\mu}\frac{dP}{dz} \tag{12}$$

2.3. Electroosmotic flow through porous media

Equations for a flow through a capillary described above can be extended to describe an electroosmotic flow q in porous media in much the same way as the derivation of the Kozeny–Carman equation from the Hagen–Poiseulle equation;

$$q = -\frac{f_s D\zeta i\rho_E}{\mu}\frac{\varepsilon}{\tau^2}f - \frac{\varepsilon^3}{kS_v^2(1-\varepsilon)^2\mu}\frac{dP}{dx} \tag{13}$$

where f_s is the shape factor of the flow path, which is the ratio of an electroosmotic flow rate through a flow path of the porous media and that of a straight capillary. i is the current density, ρ_E the specific electric resistance of the porous media (i.e. solid and liquid, viz. $E_{oz} = i\rho_E$), ε the porosity, k the Kozeny constant, S_v the volumetric specific surface area, and x the coordinate measured in the direction of the material thickness. τ is the tortuosity of the flow path, which is the ratio of a total length of a winding flow path and the thickness

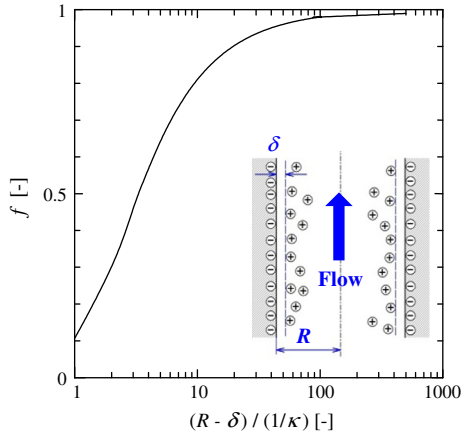

Fig. 1. Effect of the thickness of electrical double layer on electroosmotic flow rate through a capillary.