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Review

Kinetics of mechanical impurities electroseparation from dielectric liquids

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ABSTRACT

This paper deals with the problem of dielectric liquids purification. The separation process of mechanical impurities from dielectric liquids in an electric field is analyzed and an experimentally validated mathematical model is proposed for the electroseparation process. The main objective is to find a relationship to describe the kinetics of particles electroseparation, solving the problem of establishing a relationship of dependency between initial concentration and final concentration with time, and determining the electroseparation time depending on particles and liquid dielectric properties.

1. Introduction

Phase separation of disperse systems or filtration is a phenomenon presented and discussed at international conferences [1]. Currently used separators have low productivity in the case of filters or are only effective at retaining coarse particles when mechanical separators and clarifiers are used. In existing publications there is a tendency to conceive new ways of liquid fuels, oils and lubricants cleaning [2]. As the separation takes place in large tanks, it provides low operating cost when the residence time of the liquid–liquid system is long and the density difference between the phases is large. However, the situation becomes complicated for small liquid drops or solid particles, dispersed in another liquid, when the difference of density is very small and the carrier liquid is at high velocity.

Mechanical impurities separation from dielectric liquids covers a very wide range, various industrial applications being known where specific technologies are used. Currently, a prospective method for treatment of these liquids is that with application of electric fields, taking advantage of the fact that electroseparators are energy-economic, compact and show a short treatment time, so they have high productivity [2–16].

Regarding water droplets electroseparation from dielectric liquids, many authors have studied the electrocoalescence phenomenon [3–6], showing that the phenomenon of electrocoalescence can be successfully used in various technologies and industries.

The basic processes leading to coalescence of small droplets of conducting water dispersed in an insulating liquid are examined in the case of an emulsion flowing between two coaxial cylindrical electrodes and subjected to an electric field [3]. The formula giving the interaction force between two droplets and the equation governing the evolution of a polydisperse emulsion are first recalled. Expressions for the coalescence rate are derived, retaining only the induced field interaction between droplets, the characteristic coalescence time being estimated. Finally it is proposed that the shear rate plays the major role in bringing the droplets into contact.

The optimisation of the cleaning efficiency of electrostatic precipitators is important in a wide range of industrial applications. For example, in Ref. [7] it is described the development and the assessment of a complete design and optimisation method, that takes into account the flow, particle, and electric-field properties.

It has been established that the separation efficiency increases with the electric field strength and with particle (drop) size [8].

The most appropriate results of experimental research of the electroseparation process of moisture and mechanical impurities from dielectric liquids presented in this paper found in the literature are referring to the determination of efficiency for electroseparators with different electrode configurations.

Thus in Ref. [9] five different electroseparators with configurations of electrodes specially designed to retain impurities from

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dielectric liquids were tested. Regards to the analysis of impurities concentrations in examined suspension, the residual impurity concentration n dependence to the initial concentration n_0 can be exponential or relaxed [9] $n(t) = n_0 \cdot e^{-t/\tau}$, where τ is the characteristic relaxation time which depends on factors influencing the electroseparation process.

The separation of suspensions and emulsions in electric fields provides a wide range of analytical problems due to the complexity of physical phenomena encountered in the process. The process of electric charges formation in dielectric liquids was studied in Ref. [10], where the authors give some mathematical models that describe different types of electrification of dielectric liquids. In Ref. [11] the authors give a solution for the concentration, concluding that using continuous current provides satisfactory results in dielectric liquids electrofiltration.

Certain problems of electrical purification of dielectric oils (for example, transformer oil) removing micron-sized semiconducting and conducting particles are considered in Ref. [12]. It gives a solution of the problem concerning the dependence of the particle concentration on the time at the output of an electrofilter, both at a zero and a nonzero flow rate. It shows that, in both cases, the mathematical structure of the solutions is the same. Thus, it is possible to use the same formulae with the parameters of the given model. The experimental data, which are in good agreement with the theoretical results, are generalized using dimensionless logarithmic equations.

In known literature, many authors have studied particles trajectory [13,14] given by known forces as electrophoresis and dielectrophoresis, being a lack in the study of particles concentration under these forces.

Dielectric liquids suspensions and emulsions treated by electroseparation methods are analyzed in this paper. These liquids are heterogeneous mixtures under conditions of contamination with conductive or dielectric particles or water droplets of different sizes and electrophysical properties.

2. Mathematical model

We consider a suspension of particles with density ρ_2, relative dielectric permittivity ε_2 and medium-radius a in a dielectric liquid with density ρ_1, relative dielectric permittivity ε_1 and kinematic viscosity ν_1.

The electroseparation process of the particles of the suspension is made in an electric field created by an electroseparator with cylindrical symmetry and with a central electrode on which a potential difference u is applied, stationary in time. Current dependence in the circuit $I_0 = f(U)$ is known from the current–voltage characteristics of the electroseparator for the given pure dielectric fluid.

The main objective is to establish the dependence $n/n_0 = f(t)$, and to determine the electroseparation time t_p depending on particle and dielectrc liquid properties.

The mathematical model of the electroseparation process, in the conditions of addressed problem, is based on the continuity equation for particle flux vector,

$$\frac{\partial n}{\partial t} = -\mathrm{div}(n\vec{v}), \tag{1}$$

and the Poisson equation, for electric field repartition,

$$\mathrm{div}\ \vec{E} = \frac{\rho_p + \rho_i}{\varepsilon_1 \varepsilon_0}, \tag{2}$$

where $\vec{v}$ is the particle velocity vector, which can be expressed by the relation:

$$\vec{v} = \vec{u} + b \cdot \vec{F}_e; \tag{3}$$

$\vec{E}$ – electric field intensity vector in the loading-space section; ρ_p – space electric charge of the particle; ρ_i – space electric charge of ions; $\varepsilon_0 = 8.85 \times 10^{-12}$ – constant; $\vec{u}$ – dielectric liquid flow rate vector; b – particles mobility, calculated for stokes regimes of motion ($\mathrm{Re} = 2 \cdot a \cdot v)/\nu \leq 0.5$) by the formula,

$$b = \frac{1}{6\pi\nu_1\rho_1 a}, \tag{4}$$

and for $\mathrm{Re} > 0.5$ by the similar formula, obtained by linearization of resistance force in the respective interval of Re variation; $\vec{F}_e$ – electric force vector, under which particles moves between electrodes. In general [9,11,12],

$$\vec{F}_e = \begin{cases} q\vec{E}, & \text{if} \quad \vec{p} = 0,\ q \neq 0; \\ (\vec{p}\cdot\nabla)\vec{E}, & \text{if} \quad \vec{p} \neq 0,\ q = 0; \\ q\vec{E} + \left(\vec{p}\cdot\nabla\right)\vec{E}, & \text{if} \quad \vec{p} \neq 0,\ q \neq 0. \end{cases} \tag{5}$$

where $\vec{p}$ is the dipole moment and q is particle charge.

We will estimate the Coulomb force $q\vec{E}$ which acts on charged particles in comparison with the force of the external electric field $\vec{E}$ on a polarized particle $F_P = (\vec{p}\cdot\nabla)\vec{E}$. In a homogeneous electric field, the force $F_p = 0$, so this force will occur only in inhomogeneous electric fields, where $F_p = q_p \cdot 2a \quad \mathrm{grad}\, E = 2\pi\varepsilon_1\varepsilon_0 a^3(\varepsilon_2 - \varepsilon_1/\varepsilon_2 + 2\varepsilon_1)\ \mathrm{grad}\, E^2$, from where the equation

$$\frac{F_p}{qE} = \frac{(\varepsilon_2 - \varepsilon_1)a}{3\varepsilon_2 E} \cdot \mathrm{grad}\, E, \tag{6}$$

for $E \geq 1$ kV/cm, grad $E \leq 1$ kV/cm^2, $\varepsilon_2 \geq \varepsilon_1$ and $a \leq 300$ μm not exceed 0.01. So, the force F_p will not contribute to the electroseparation process. The force F_e which acts in the electroseparation process is the coulomb force $\vec{F}_c = q\vec{E}$, even if generally, according to equation (5), $\vec{p} \neq 0$ and the electric field in inhomogeneous.

We further examine whether the kinetics of charging of particles in accordance with the formula of Pautonnier $q = 4\pi\varepsilon_1\varepsilon_0 E_0 a^2 (1 + 2(\varepsilon_2 - \varepsilon_1/\varepsilon_2 + 2\varepsilon_1))(e \cdot n_{i0} kt/4 - \varepsilon_1\varepsilon_0 + e \cdot n_{i0} kt)$ influence the kinetics of electroseparation. Given the usual values of the parameters entering in the non-stationary relationship ($\varepsilon_1 = 2.4$; $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m; $e = 1.6 \times 10^{-19}$ C; $k = 2.1 \times 10^{-4}$ m^2/(V s) and $n_{io} = 2.5 \times 10^{-12}$ m^{-3}), we found that in the time equal to 1, 60 and 120 s the particle will be charged with 50, 98.4 and 99.2% of its maximum charge, therefore the characteristic time of charging is much smaller than the duration of electroseparation process, which is over 20 min [9].

Next, we will keep the stationary part of the charge, $q = \mathrm{const}$:

$$q = 4\pi\varepsilon_1\varepsilon_0 E_0 a^2 \left(1 + 2\frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_2 + 2\varepsilon_1}\right) \tag{7}$$

The spatial electric charge $\rho_p + \rho_i$ in Poisson equation (2) is determined on the following considerations.

The ion density ρ_i in the cross section s of the tube of force is determined from the condition $i_1 = \mathrm{const}$:

$$\rho_i = \frac{i_1}{kES}, \tag{8}$$

where i_1 is the ion current intensity.

From the continuity equation of particles flux,

$$f = qbEnS = \mathrm{const}, \tag{9}$$