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Electrocoalescence in non-uniform electric fields: An experimental study

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ABSTRACT

The method of electrostatic force-assisted phase separation is widely used in the chemical industry. The fast and clean separation capabilities make electrocoalescence a favorite among the other competing phase separation techniques. In the present study, we experimentally investigated the relative merits of symmetric and asymmetric non-uniform and uniform electric fields in electrocoalescence. Three different types of emulsions are studied: (i) a perfectly conducting (PC) phase dispersed in a perfectly dielectric (PD) medium, (ii) a leaky dielectric (LD) phase dispersed in another LD phase of higher electrical conductivity, and (iii) a LD phase dispersed in another LD phase of lower electrical conductivity. The coalescence behavior of each emulsion in the non-uniform electric fields is analyzed and the results are compared with that in a uniform field. The observations show that a non-uniformity as well as asymmetry of electric field can affect electrocoalescence in a nontrivial way and is sensitive to the drop-medium system, specifically pin-plate, quadrupole and annular electrode configurations are found to be advantageous over uniform field in PC drops in PD medium, less conducting LD drops in more conducting LD medium and more conducting LD drops in less conducting LD medium, respectively.

1. Introduction

Stable emulsions have been an issue of concern in many chemical processes. In the petroleum industry, naturally stable emulsion of water in crude oil can pose several problems during its processing. In liquid–liquid extraction, a stable mixture of extract and raffinate phases take a long time to separate by gravity. There exist many techniques of phase separation; e.g. gravitational or buoyancy separation, centrifugation, chemical treatment, membrane separation, etc. [1–3]. However each of these conventional techniques has some disadvantages; e.g. gravity settling takes long time for dispersed phase to settle if the drops are very small in size, chemical treatment affects the quality of separated water and also causes pollution, mechanical energy and thereby shear may not be very efficient in coalescence, etc. The use of electrostatic energy has been considered as one of the most effective and clean methods of phase separation. In addition to separation of water to a desired level, low energy consumption and lack of necessity of further purification of the separated phases make the electrostatic method worthy. Electrocoalescence is the de-facto method in desalting operations wherein minute water droplets of size below 50 μm are separated from crude oil [4].

Started in early 20th century, extensive research has resulted in fundamental understanding of many complex problems in electrocoalescence that have helped to make the technology more efficient, faster and the devices more compact [5]. Applying an electric field induces free charge separation in a conducting water drop resulting in a dipole and the consequent dipole–dipole interaction between neighboring drops in an emulsion enhances the coalescence rate. In addition to the dipolar attraction, an applied electric field can induce macroscopic flow currents due to movement of drops or due to tangential stresses in leaky dielectric systems which increase the probability of inter-drop contact. The coalescence of two drops in an electric field is assume to occur in three stages [5,6]; in the first stage, two drops are attracted towards each other on application of the field. The second stage involves squeezing of the medium fluid from the film between leading faces of the approaching drops. When such an interstitial film becomes microscopically thin, its break up and consequent coalescence of two drops occurs in the third stage. There are several parameters that determine the coalescence dynamics in the presence of an electric field. The factors such as the magnitude and type of an applied field, electrical and physical properties of the fluids, impurities in the emulsion, flow or turbulence, drop size, dispersity, etc., govern the kinetics of electrocoalescence. The role of such parameters has

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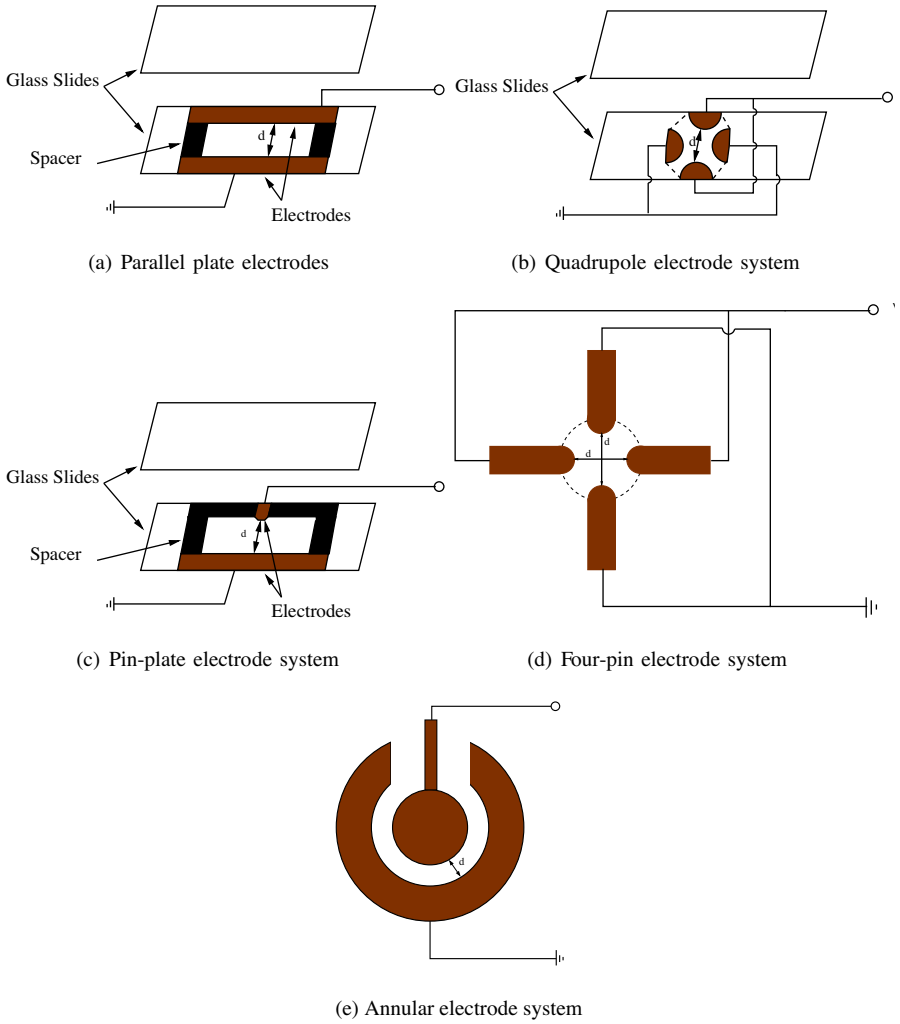
been a topic of investigation in the majority of scientific studies in electrocoalescence [7–10].

Application of moderate electric field to an emulsion leads to several phenomena such as chain formation, partial coalescence, non-coalescence and receding of about to coalesce drops, drop breakup, etc., which are known to adversely affect the rate of electrocoalescence [5]. In an electrocoalescing emulsion, drops can arrange into chains aligned in the direction of the applied field [11,12]. The interfacial stability of the drop interface often promotes chain formation. Such chains of droplets not only slow down the coalescence rate, but can also extend to the electrodes resulting in to short circuiting. The formation of fine progeny droplets during drop-interface or drop–drop coalescence is termed as partial coalescence [13]. This phenomenon introduces new drops in the emulsion which are difficult to separate owing to their very small sizes. The application of an electric field induces drop–drop approach, but cannot guarantee coalescence. It has been observed that in certain conditions (especially under strong applied electric fields), coalescing drops retreat after their contact [14]. In another undesired effect, after coalescence, if the field at the resulting drop interface exceeds the critical field limit, $E_c = 0.648\sqrt{\gamma/2a\epsilon_m}$, a drop can further break into smaller droplets [15]. Here, γ is interfacial tension, a is drop radius and ϵ_m is permittivity of medium fluid. Such adverse effects need to be overcome to speedup the electrocoalescence process.

In addition to water separation from crude oil, electric field can also be employed for phase separation in systems involving a leaky dielectric (LD) fluid dispersed in to another LD medium. The examples include fractionation of mixed oils [16], electrorheology of electro-magneto responsive fluids, polymer blends, etc. Electrorheological (ER) fluids are LD–LD suspensions which display a change in rheological properties e.g. shear thinning or thickening under the influence of an electric field [17,18]. Such fluids are used in the active control devices such as dampers, shock absorbers, clutches, brakes, etc. The preparation of a polymer blend involves dispersing one polymer in to another in order to acquire the desired properties from the resulting new polymer. Control over the droplet size in a blend plays a key role in deciding the properties of the resulting polymer. Electric fields can also be used to precisely regulate the dispersed phase drop-size distribution. Furthermore, during recycling, electrocoalescence can be used to separate a dispersed polymer phase from the molten blend. An in-depth understanding of the electrocoalescence in an oil-in-oil emulsion can help to control the size distributions in the ER fluids as well as in the polymer blends.

Electrocoalescence has been construed as separation of two liquid phases by applying uniform electric field. The electric field employed in the previous electrocoalescence studies was predominantly of uniform kind. Very few studies in the literature discuss the use of non-uniform electric fields for phase separation. Pearce



(a) Parallel plate electrodes

(b) Quadrupole electrode system

(c) Pin-plate electrode system

(d) Four-pin electrode system

(e) Annular electrode system

Fig. 1. Schematics of various electrode systems used to induce the uniform and non-uniform electric fields. Electrode-electrode separation, $d = 5$ mm in all the electrode configurations.