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Short communication

Electrostatic enhancement of coalescence of water droplets in oil: a review of the technology

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Abstract

The technology for electrostatic enhancement of coalescence of water droplets in oil emulsions is critically reviewed. Historically, the electrostatic coalescer was invented for the petroleum-related industries in California [US Patent 987 115 (1911)]. Nowadays, this technology is generally considered for the separation of an aqueous phase dispersed in a dielectric oil phase with a significantly lower dielectric constant than that of the dispersed phase. Various designs have been introduced, with most using alternating current (AC) electric fields with mains frequency (50 or 60 Hz). The direct current (DC) electric field has been less common in the past as compared to the AC. In 1981, the concept of pulsed DC electric fields was introduced, together with insulated electrodes [Trans. IChemE 59 (1981) 229–237; UK Patent 217 1031A (1986)]. Since then, this has become more common in the electrocoalescence technology. Pulsed DC and AC fields are especially useful, when the aqueous phase content of the emulsion is high, to prevent short-circuiting between the pair of electrodes. Processing of oil from old wells is a good example, where the volumetric water content could vary significantly. Reported work by some workers indicates the existence of an optimum frequency, which depends on the electrode coating material, its thickness and the liquid emulsion composition. This is however, a contentious issue which has not been completely resolved. The characteristics and geometry of the electrode system (generally cylindrical or plate) influence the performance of the electrostatic coalescer, and are closely related to the type of the applied electric field and the emulsion used. There are basically two types of electrode: uninsulated electrode and insulated electrode. Combination of electrocoalescence and mechanical separation (e.g., centrifugal force) has also been introduced. Heating and the addition of chemicals have been shown to further enhance the electrocoalescence of water droplets. Other methods that can be combined with the electrical treatment are filtration, methods employing high pressure and temperature, and mixing. This review paper also looks at some of the current specific industrial applications using the electrocoalescence technology. Besides the oil and petroleum industries, this technology has potential applications in the edible oil industries such as palm oil, sunflower oil and vegetable oil processing. Most of the currently available equipment is very big and bulky, having a large inventory of emulsion. Therefore, we see the future trend for new developments to be in the direction of inventing small portable devices, incorporating features such as optimum electric fields and combined electrical and centrifugal forces to further enhance the separation of water-in-oil emulsions. Furthermore, a better understanding of the fundamentals of electrocoalescence will enable a better design of the geometry of the electrodes, of the flow field with respect to the electric fields, the type of dispersion used and the type of the applied electric field.

Keywords: Water-in-oil emulsions; Dispersions; Electrocoalescence; Electric fields; Frequency; Pulsed direct current; Alternating current; Separation; Centrifugal force

1. Introduction

In many chemical processes, efficient removal of a dispersed water phase from a continuous oil phase is highly desirable. Currently, there are several available methods, such as chemical demulsification, gravity or centrifugal settling, pH adjustment, filtration, heat treatment, membrane separation and electrostatic demulsification [5,6]. Each of these methods has its own advantages and disadvantages. For example, the use of chemical demulsifiers can modify the water/oil interfacial properties, thus allowing water droplets to coalesce more easily into larger droplets. However, additional problems are encountered in the removal of the demulsifiers from the aqueous and oil phases. The pH effect can be utilised to separate oil-in-water emulsions, but it is usually not effective in breaking water-in-oil emulsions.

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Centrifugation, an effective method for some emulsions, has a high operating cost. Heat treatment can reduce the viscosity of the oil, thus allowing any water droplet to fall more rapidly through the oil phase, and to help in the separation of any entrained gas in the crude oil. However, heat treatment and chemical treatment are rather expensive, and heating has a tendency to result in high fuel consumption.

The slow rate at which liquids may be naturally separated in many water-in-oil type dispersions has important consequences in many commercial operations [7,8]. For example, water-in-oil type emulsions are readily formed in the production of crude oil, causing problems at different stages of the production. Corrosion of pipes, pumps and other processing equipment, the complications due to increased emulsion viscosity resulting from finely dispersed water droplets in the crude oil and the deactivation of catalysts by water droplets are consequences of the presence of water [9]. Furthermore, the cost of transporting water in pipeline or tanker, and the extra processing equipment required to produce quality crude oil add to the production cost. Therefore, there are a number of commercial reasons for removing this emulsified water from the crude oil.

External electric fields have been applied extensively to break water-in-oil emulsions. Historically, the electrical treatment has been established since the pioneering work of Cottrell and Speed [1] and Cottrell [10]. The patent information in this field is largely about methods for dehydrating crude oils, frequently in line with the desalting procedure [11]. The electrostatic treaters use the electric field to enhance coalescence of aqueous droplets in crude oil, improving phase separation, although the exact way in which this occurs is not yet clearly understood [12]. Eow et al. [12] provide a comprehensive review of the fundamentals of the coalescence process. In this paper, we restrict the review to its technological aspects, methods and apparatus proposed for the process.

The application of electrocoalescence is largely concentrated in the oil and petroleum industries where high voltage alternating current (AC) fields and, to a lesser extent, direct current (DC) fields are used for the separation of water droplets from crude oil [2,13–18]. The conventional electroseparators are huge, as large residence times are required for the electrocoalescence regions and settling zones to separate the enlarged water droplets from the crude oil. However, this could cause complications for offshore platforms as platform structures usually have limited space [7,13,19,20]. This limitation has to be addressed during platform planning and construction so that sufficient space can be provided for the separation equipment. Therefore, information about crude oil tendency to form emulsions [21–23] and reliable methods of emulsion separation are essential for the above purposes. Higher operating costs also arise from the need to process higher emulsion throughputs in a unit.

Optimisation of the coalescence process therefore would be able to reduce the residence time of the droplets in a given physical system, thereby increasing the volumetric throughput and enabling the utilisation of smaller and, consequently, cheaper units. With these in mind, we critically review the currently available methods to see whether they can be beneficially manipulated and improved in order to achieve greater separation efficiency and wider application.

2. Review of the available technology

Electrical methods for dehydrating crude oil emulsions have been the subject of a large number of patents, relating to both technique and apparatus. These patents are summarised in the following and in Fig. 1.

Generally, an electrostatic coalescing vessel is made up of a tank equipped with electrodes, at least one of them is earthed and at least one other electrode is suspended by an insulator, to which an electrical potential is applied. However, some specifically designed electrical systems using AC power have all live grids as electrodes. Several possible mechanisms for electrocoalescence have been identified [13], based on the attraction of opposite charges due mainly to polarisation effects, and net charges if they are present. The resultant bigger droplets settle more rapidly to the bulk interface. Several types of electric field have been demonstrated to be effective for electrocoalescence, such as AC fields [1,10], pulsed AC fields [24], DC fields [25] and pulsed DC fields [26,27]. The AC electric field has been used from 1911 [10] up to the present time [28]. The application of pulsed DC electric field was introduced by Bailes and Larkai [2].

Emulsions from crude oil and some other emulsions may contain water concentration of above 20% [4,17,24,29,30]. Therefore, it is usually difficult to apply electric fields using only bare metal electrodes because the large amount of aqueous droplets will cause electric short-circuits between the electrodes [31]. This can be solved by insulating the high voltage electrode so that those conduction passages will only produce a localised decrease of the electric field strength rather than a total collapse of the field strength throughout the electrode region [29–32]. However, in this case a time-varying electric field is required.

At present, most of the inventions summarised in Fig. 1 are aimed at providing a method and apparatus for separating the components of an emulsion, which can allow improved separation rates to be achieved. There are also inventions that combine the effects of centrifugal force and electrostatic coalescence of water droplets to separate the dispersed water droplets from the continuous oil phase without using chemicals or heat treatment for decreasing the viscosity of the liquid–liquid dispersion system [31–36]. The need for the reduction of the oil viscosity is avoided, by applying centrifugal force and electrocoalescence simultaneously to enhance the separation of water from the viscous oil; cf. Figs. 2 and 3. In Fig. 2, an aqueous electrolyte–oil emulsion is fed into a rotating cylinder via plastic tubes and a distributor, removing the electrolyte from the periphery of

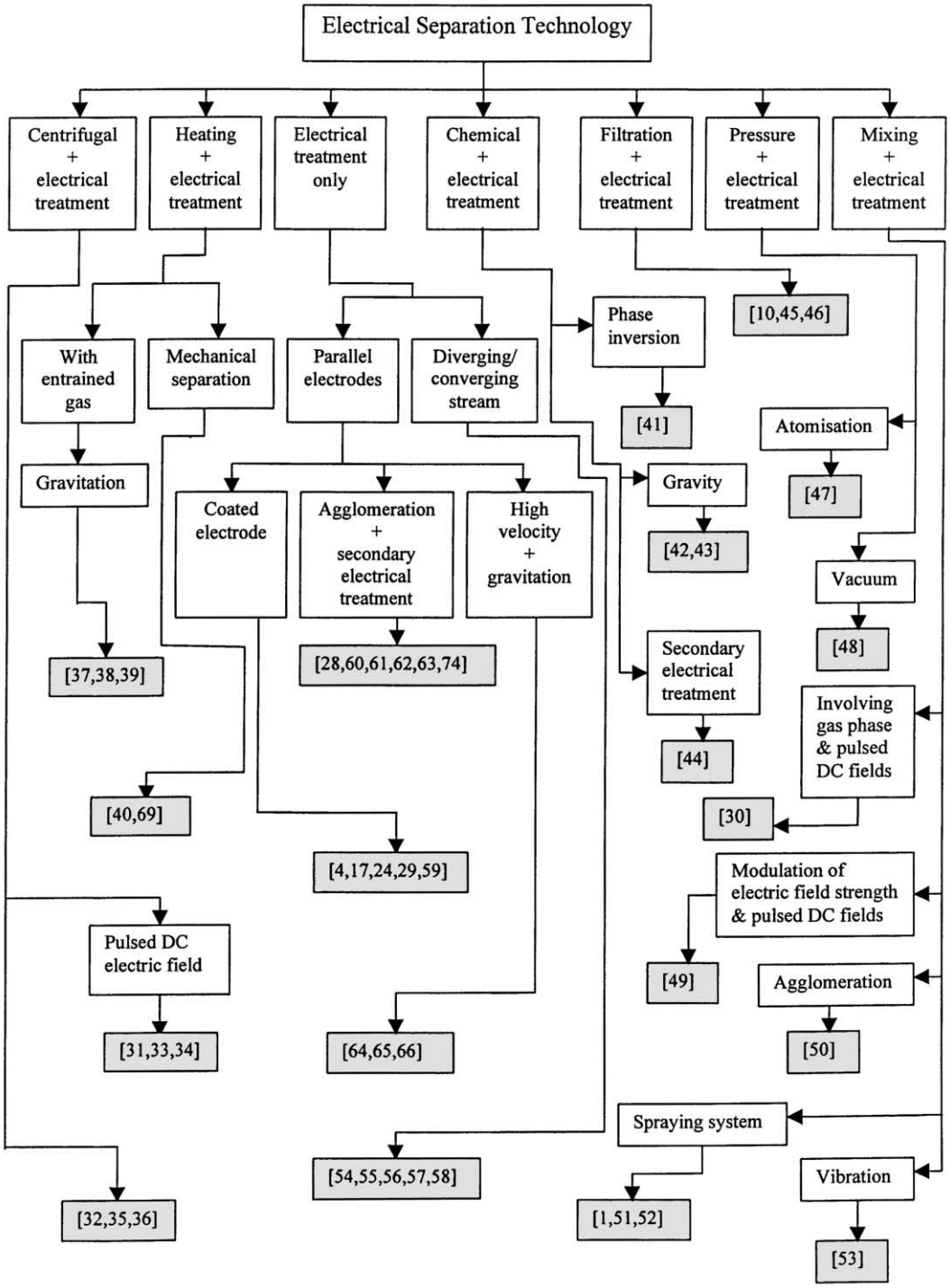

Fig. 1. Various combinations of the electrical separation technology.

the cylinder, and the organic component from the adjacent tubes. The emulsion is separated by the application of a radial electric field and a centrifugal force simultaneously to produce a bulk interface perpendicular to the direction of the electric field and centrifugal force.

The electric field is applied to cause the coalescence and enlargement of the dispersed aqueous droplets to a sufficient size for the centrifugal force to separate the droplets without producing sufficient shear force to break them up. Centrifugal forces can also be applied to separate the heavier fluid from less dense fluids in a mixture. Basically, the dispersion is tangentially injected into a cylindrical-walled vessel to enable the dispersion to flow circumferentially in the vessel. In this manner, the water droplets are caused to

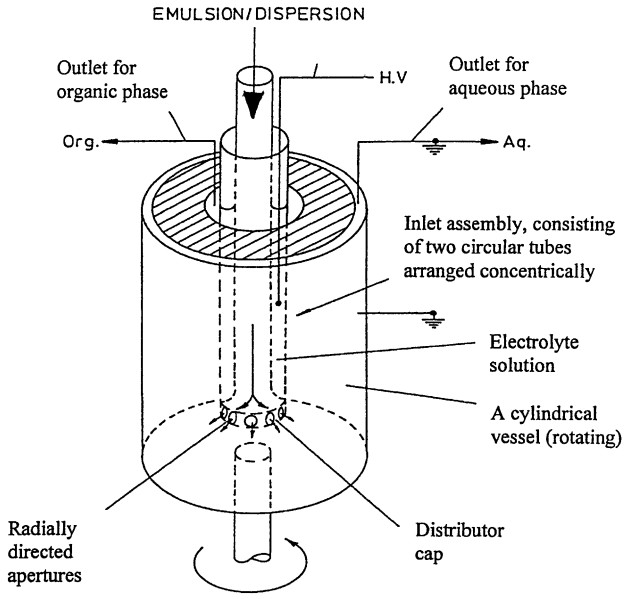

Fig. 2. Apparatus for electrostatic and centrifugal separation of liquid dispersions [33].

migrate towards the vessel wall. The high voltage electrode is positioned axially in the centre of the vessel [31]. Due to centrifugal action, the oil around the electrode has a much lower water content. This allows the use of thinner insulating material, and reduces the electric field drop across the insulator. In some applications, it has been proposed that the centrifugal forces can be utilised to eliminate the need for electrode insulation [31]. In this geometry, the electric field is non-uniform (radially divergent) and could cause drop break-up and/or migration, the latter due to dielectrophoresis. The centrifugal action, however, quickly separates the water droplets in the high electric field region, thus avoiding the above detrimental effects. However, there is also a tendency with high centrifugal motion to stabilise the emulsion by shearing and turbulent mixing [33].

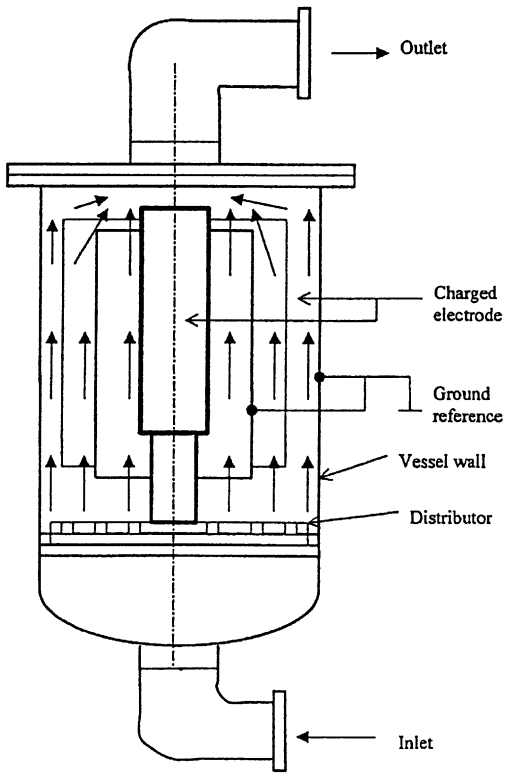

Fig. 3. Parallel-flow EPIC configuration [34].

Fig. 1 shows the combination of electrical treatment with heating, which can be further subdivided into two categories: entrained gas involvement with gravitation [37–39], and mechanical separation [40]. A device, patented by Bull [37] and termed a “treater”, separates electrostatically and/or mechanically an emulsion flowing through a horizontal metal vessel. A significant number of the aqueous droplets are charged by contact charging as the mixture flows through the multi-electrode system. Convective charge transfer by the oil has also been suggested as a possible mechanism here [37]. The charged droplets then flow through a coalescing device consisting of inclined tubes arranged in a bundle. The tubes provide resistance to the emulsion flow so that contact between the aqueous droplets and the internal walls of the tubes is enhanced. Attached to the tube walls, the aqueous droplets will lose their charges and accumulate to form aqueous bulk phase at the bottom of the tubes.

For heating, usually an electric conductor of relatively high resistance, in the form of a coil, is submerged directly in the emulsion [39]. The mixture is heated up to about 200 °C, converting the water droplets into steam. A part of the oil is also transformed into vapour in this process, but this is condensed at a later stage. Heating also reduces the viscosity of the oil, thus facilitating the rising and escape of the water vapour.

For mechanical separation, Sublette [40] utilised a mechanical coalescence medium, e.g., an inclined surface separator, after a system of charged electrodes, the latter shown in Fig. 4. The collection surfaces are inclined to enable the accumulated aqueous droplets to move along the surface and to encounter other droplets. Coalescence of the droplets then occurs, producing larger droplets which leave the surface.

The combination of chemical and electrical treatment can be further divided into three types: phase inversion [41], gravitational settling [42,43], and secondary electrical treatment [44], as shown in Fig. 1. While various theories regarding the effect of chemicals on the breaking of petroleum emulsions have been advanced, the most general theory is that the coalescence of the dispersed phase in the emulsion results not from any distinctly chemical reaction but from some physical effects of the chemicals, which change the interfacial properties of the two phases, thus facilitating droplet–droplet coalescence. Chemical compounds which have been found most useful are those which have the property of liberating free chlorine radicals, such as chlorinated oils, chlorocosane, chloramine, toluene and hydrochlorites

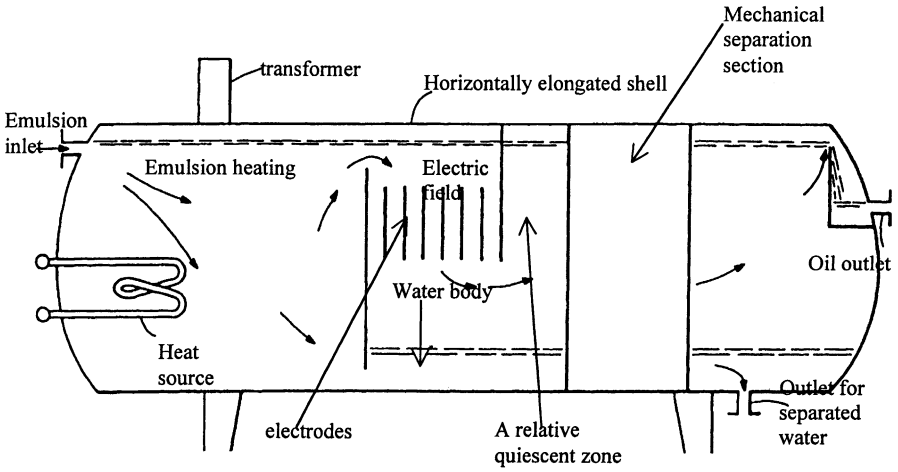

Fig. 4. A sectioned elevation of a horizontally elongated vessel having an electrode system and a mechanical inclined surface separator [40].

[42]. However, Herbsman [42] did not give any explanation for using these chemicals.

Some methods have also utilised filtration in combination with electrical treatment [10,45,46]. For example, Cottrell [10] applied a thorough initial wetting of a filter septum with a liquid that is miscible with the dispersed liquid phase, thus establishing a continuous channel for the drainage of the dispersed liquid phase through the wetted septum, a direction usually traverse to the general flow of the emulsion. This septum formed a part of an electrode system connected to an AC of sufficiently high voltage to cause coalescence of the dispersed droplets, thus separating the two liquids from each other.

As shown in Fig. 1, there is also a method using pressure in combination with the electrical treatment [47,48]. The method of demulsification at a pressure below atmospheric produces a much quicker separation [48]. The emulsion droplets contain entrapped gas, which expands rapidly when subjected to low pressure. When the emulsion is subjected to the influence of the electric field, a much more rapid coalescence action is obtained under low pressure, although the reasons are not clearly understood. Sometimes the application of low pressure is accompanied by heating for which further enhancement of coalescence and separation has been reported [48]. It is claimed that under these conditions, the oil expands more than water, thus increasing the difference in specific gravity between them, and this will greatly accelerate the separating action [48].

The combination of mixing and electrical treatment can be subdivided into several categories: gas phase involvement [30], electric field strength modulation [49], coalescence [50], spraying system [1,51,52] and vibration [53]. Generally, mixing is used to prevent the formation of short-circuiting chains of water droplets, or to break-up such existing chains. In the method of Cottrell and Speed [1], e.g., the emulsion enters the electrical separation vessel as streams impinging on the upper surface of the liquid in the vessel, causing a stirring of the surface and a thorough mixing of the in-flowing emulsion. The emulsion then flows downward between the electrodes.

For the electrical treatment alone, there are several variations as indicated in Fig. 1. Firstly, there is uniform flow with parallel electrodes, as well as non-uniform flow due to diverging and/or converging streams [54–58]. The system of parallel electrodes can be further divided into systems with coated electrodes [4,17,24,29,59], systems with a combination of coalescence and secondary electrical treatment [28,60–63] and systems with a combination of high inertia and gravitational forces [64–66]. The secondary electrical treatment here refers to a second set of electrodes which are usually located at the exit of a vessel.

For the system with coated electrodes, the electrodes have an insulating material having a typical dielectric constant of about 3 and a hydrophobic surface contacting the emulsion [29]. However, under the conditions of low electric field when the coalescence is not efficient, the precipitated aqueous phase may form a layer of viscous, sponge-like emulsion, containing a small percentage of the surfactant containing oil phase, hence reducing the separation quality, as the aqueous phase may contain a small quantity of oil [29]. Under high voltages, Hsu et al. [29] observed that the formation of spongy emulsion and decomposition of the oil phase are minimum. The laboratory-scale electrostatic coalescer used by Hsu et al. [29], as shown in Fig. 5, has an interesting configuration. The coalesced aqueous phase at the bottom of the coalescer is electrically grounded to form an electrode. The high voltage electrode comprises a piece of Pyrex tubing, bent into a shape as shown in Fig. 5, or bent into a grid shape. The horizontal portion of the tube is filled with an electrolytic solution to transmit high voltage from a flexible conductor connected to an external high voltage supply. The vertical stems of the tube are filled with transformer oil. The external of the glass tube is coated with a very thin layer of fluorinated ethylene-co-propylene

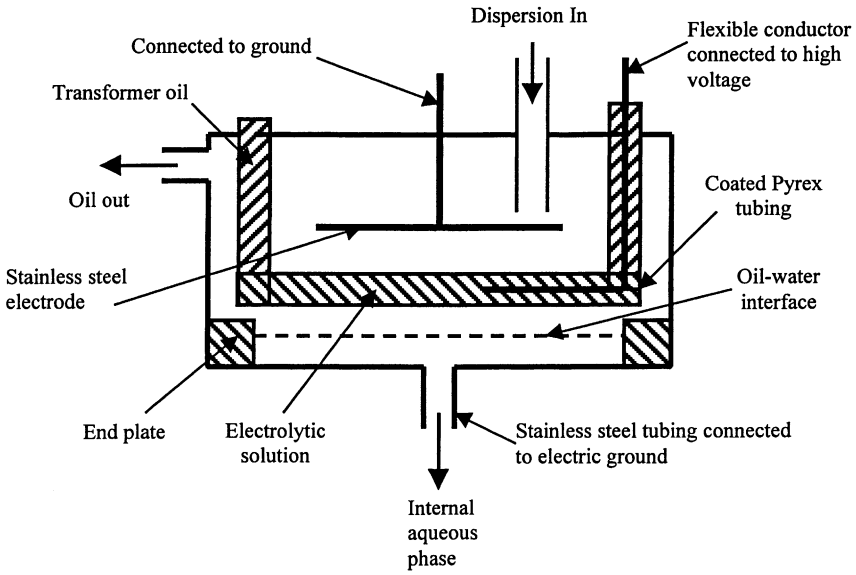

Fig. 5. Schematic illustration of the continuous coalescing apparatus [29].

to reduce the water wettability of the surface. The grounded electrode is essentially a flat stainless steel wire mesh. An AC electric field with frequency 60–1000 Hz is applied. Hsu et al. [29] claim that the coalescer with its specific set-up is effective for breaking relatively stable synthetic emulsions in liquid–liquid extraction processes. The maximum coalescence rate is shown to be a function of the applied potential, the position of the feed inlet, and the separation distance between the insulated electrode and the oil–water interface level in the coalescer [29], with an optimum separation distance to minimise the accumulation of sponge emulsion.

3. Factors affecting electrocoalescence

The main objective of an electrocoalescer is to enhance the coalescence rate of water droplets in a water-in-oil emulsion so that these droplets can grow to a certain size in order to be separated from the continuous phase by gravitational or centrifugal methods. Several important features of a typical electrocoalescer are therefore critically discussed below.

3.1. Electric field

An electric field can only be used to increase the coalescence rate of a dispersed phase in an emulsion when the continuous phase has a much lower permittivity than the dispersed phase [1,10,33,39,63]. At the same time, the continuous phase should have a low conductivity and act as an insulator between the two electrodes.

The means of applying a high electric field includes at least a pair of electrodes, one at a relatively high voltage, and the other at a low voltage (preferably earthed). In addition, this high voltage may be pulsed [4,30–33]. AC, DC, pulsed DC or combinations of them are being utilised in the separation of water-in-crude oil dispersions or emulsions. Each field type acts according to different mechanisms in enhancing phase separation by droplet–droplet coalescence [13,67]. AC field has predominantly a polarising effect, whilst some electrophoretic effects may also be present for the DC field. As mentioned earlier, under a pulsating electric field, chains of droplets can be observed during the periods of high voltage followed by coalescence during the periods in which the voltage is reduced. A feature to consider in choosing the right type of electric field is the volume content of the dispersed phase (i.e. water) as it is electrically conductive and may result in short-circuiting of the system [49]. AC electric fields are usually utilised when dealing with crude oils. However, when the continuous phase is a distillate and the dispersed phase is an acid or caustic, a combination of AC–DC electric fields is usually employed to avoid short-circuiting [17].

The polarisation phenomenon induced by the electric field produces dipole–dipole forces. These forces are effective over short separation distances, and significantly enhance droplet–droplet coalescence [13,68]. The droplet–droplet collision rate is further increased by the hydrodynamic flow and mixing of the emulsion. Enlarged droplets will then separate out from the continuous oil phase under gravitational action.

Normally, an AC field is used for uninsulated electrodes in a water-in-oil emulsion having a relatively high dispersed phase content [67]. The AC field presents further important technical advantages. For example, the danger of electrolytic corrosion can be eliminated [1,10]. Typical, applied values of the AC electric field strength vary according to the water content of the emulsion and the overall system arrangement; Alden and Eddy [69] used field strengths between 60 and 180 kV/m.

The DC electric field is able to produce rapid electrophoretic motion of water droplets. The water droplets may be charged initially by direct contact charging with the electrodes [17,25]. The increased rate of droplet–droplet collision is then caused by the droplets moving rapidly between the electrodes. As a result, the rate of droplet–droplet coalescence becomes more significant. The droplets can also form an aqueous layer on the electrode surfaces. DC electric fields have been applied with distillates and condensates which are relatively non-conductive. However, the DC electric field is generally less commonly used than the AC and pulsed DC fields.

Together with the AC electric field, the pulsed DC electric field has been utilised extensively since 1986. Pulsating DC electric fields have been receiving a lot of attention lately, especially when utilised together with coated electrodes [4,30,32]. Like the AC separation methods, pulsed DC systems involve induced dipoles on the water droplets, leading to attraction and coalescence between adjacent droplets. An optimum frequency for the optimum coalescence rate has been reported in a given physical system [30,31,33], presumably due to differences in electrical and mechanical relaxation processes.

Pulsed DC field with insulated electrodes has been developed for emulsions with a high dispersed phase content [4,30,34]. Without any electrode insulation, the high dispersed aqueous phase content can lead to short-circuiting of the electrodes. Typical values of the applied pulsed DC electric field strength also vary depending on the water content of the emulsion and the overall system arrangement; Bailes and Larkai [4] applied a DC field of 110 kV/m pulsed at less than 1 Hz.

With some electrode geometries (such as parallel plates), the electric field is uniform. However, this may not be the case with other electrode geometries, which can have consequences such as droplet break-up in the high field regions and also droplet migration (dielectrophoresis) in the non-uniform field. According to Williams and Bailey [70], if the electric field strength becomes too high, various droplet break-up mechanisms are likely to become operative, resulting in re-emulsification. The onset of instability is reached when the interfacial tension effect is overcome by the electric-induced interfacial stress [70]. The latter depends on the way the droplets are being charged.

Several design challenges are encountered in the industrial application of pulsed DC fields [71]. Firstly, either a vertical or a horizontal set-up has to be chosen, depending upon whether the objective is to operate the equipment as a coalescer or as a separator. A separator is more suited to horizontal operation as it requires a large bulk interface area for droplet–interface coalescence [34]. In a coalescer, droplet–interface coalescence is usually less important than droplet–droplet coalescence. Therefore, a vertical flow coalescer can equally accomplish the task, with having the additional advantage of a smaller footprint [34].

3.2. Frequency

Brown and Hanson [72] observed an optimum frequency at which coalescence occurs more readily, and further suggested that mechanical vibrations and cavitation within the droplet also influence film rupture and coalescence. More recently, the existence of an optimum frequency has also been reported by Bailes and Larkai [2,3,26]. The selection of an optimum frequency may therefore be important, especially at low applied potentials and depends on the coating material and its thickness, and liquid dispersion composition. However, it is unclear whether the existence of an optimum frequency is due to the limitation of the power supply circuit or the electromechanical relaxation of the dispersion.

In the absence of an insulating coating, the optimum frequency is more dependent on the electrical properties of the continuous liquid phase. In the case of pulsed DC field, besides the optimum pulse frequency, the ratio of the duration of high field period, ‘time-on’ to no field period, ‘time-off’ is also important. The best condition found for effective coalescence is that the ‘time-on’ should be equal to the ‘time-off’ [3,34]. Nevertheless, Galvin [67] suggested that the voltage rise and fall time constants of the power supply circuit were more important. The rise-time constant is controlled by the electrical resistance of the circuit and capacitance of the electrocoalescer. The coalescence performance improves as the electric field strength across the dispersion is increased, due to the increase in the forces causing coalescence.

The magnitude of the applied frequency depends greatly on the type of electric field, as well as on the arrangement of the electrodes. For AC electric fields, Roberts [59] used a frequency between 60 and 10,000 Hz, while Hsu et al. [29] applied an AC field having a frequency of about 60–1000 Hz between the insulated electrode and the earthed aqueous layer at the bottom of the coalescing zone. However, a much lower frequency is usually used with pulsed DC electric fields; Bailes and Larkai [4] applied an electric field pulsed at a frequency less than 1 Hz; Bailes and Watson [33] used a pulse rate of 25 Hz in a rotating cylindrical coalescer, whilst Bailes [30] employed an optimum frequency of 15 Hz in a gas bubble-insulated electrode system. Therefore, there seems to be no common value of applied frequency for all the systems.

3.3. Electrode

Generally, two main designs of coalescer are common [73]; cellular units which may consist of coated or uncoated electrodes and either internal or external settlers, and tank units with bare electrodes in which coalescence and settling take place simultaneously, as commonly used in the oil industry. Cellular systems are more often found in solvent and liquid membrane extractions.

The characteristics and geometry of an electrode (generally cylindrical or plate) determine the performance of the

electrostatic coalescer. The type of electric field and the emulsion will influence the choice of the above features.

The maximum distance between the electrodes is limited by electrode edge effects (i.e. fringing fields) and the potential that must be applied to create a sufficiently high electric field strength [39,58,63,66]. In the former, as the electrode spacing is increased, fringing electric field becomes more significant. In the latter, transformer design and electrical circuitry are influential [17,60,74]. The electrodes are commonly arranged as either closely spaced long electrodes or widely separated short electrodes.

The choice of electrode geometry is another aspect that should be considered. Safety and practical considerations usually dictate the design of a coalescer to be a cylindrical pressure vessel when the emulsion is at high pressure [31] and temperature [37]. A cylindrical electrode mounted co-axially in a vertical coalescer turns out to be a simple and yet effective arrangement [57].

In applications of DC electrofining, bare electrodes are usually arranged vertically, allowing droplet growth and sedimentation to take place within the space between the electrodes. Some AC coalescers contain metal grid electrodes positioned horizontally, thus allowing water droplets to pass through the electrodes. Multiple electrode arrangement is usually used here with varying electric field strength. Initial stages use the highest electric field strength to cause most rapid coalescence, whilst later stages have lower field strength to reduce short-circuiting due to the presence of large droplets. Generally, an uninsulated electrode may be used efficiently when the content of the dispersed phase is less than or about 15% of the emulsion [31]. Above this limit, short-circuiting may occur [30,35,63,66]. However, in some operations, the use of the centrifugal force may eliminate the need for an insulated electrode [1,31,32].

For bare electrodes, the high water content tends to over-stress the electrical equipment due to the development of direct conductive passages between the electrodes. Short-circuiting and the collapse of the electric field will certainly remove the coalescing force. On the other hand, an insulated electrode will reduce the electrical potential at the electrode emulsion interface [24]. One possible solution to this problem is the combination of an insulated electrode and a pulsed DC electric field. Examples of insulating materials are ABS plastics, TUFNOL [33] and PTFE [15], and various inorganic and organic materials such as glass, quartz, ceramics, various refractory metal oxides, and various rubbers and plastics having the required dielectric constant of about 4 [29].

The insulation should also have an electrical breakdown strength sufficient to withstand the voltages used [29]. Hydrophobicity may be inherent in the insulation material or it may be achieved by coating or covering the insulated electrode with a suitable material having a specific free surface energy below 40 mJ/m^2 [29]. Various surfaces may be treated with silanes which will result in surfaces having a specific free surface energy of about 35 mJ/m^2. The hydrophobic surface modification of the insulated electrode can be very thin typically of molecular length, such as alkoxysilane-coated glass. An electrode system can be designed to have a number of coated elements forming the electrode insulation for treating a water-rich dispersion and a number of uncoated electrodes for a water-lean dispersion. This electrode system has been found to allow water contents in the oil phase and oil contents in the water phase (entrainment) to be reduced to much lower levels than those obtained with the fully coated electrode systems.

Another example of an insulated system is the use of gas bubbles [30], which are injected into an emulsion whilst the emulsion is under the influence of an applied electrostatic field. The electrodes are vertical in this case, and the swarm of gas bubbles shields the high voltage electrode, reducing short-circuiting. Droplet–droplet coalescence in the oil continuous phase is then enhanced [30]. The gas bubbles also seem to form channels through the emulsion, which assist in providing pathways through which the coalesced droplets can move rapidly towards the bulk interfaces [30]. The gas bubbles therefore improve both the rate of droplet–droplet coalescence and the rate of droplet settling from the dispersion. However, the ratio of the inert gas to liquid flow rates is very large and residence time of the emulsion is long.

4. Current and potential industrial applications

Many industries nowadays employ the electrostatic coalescence technology, not just to enhance the separation of emulsions of the water-in-oil type, but also to operate in a more environmental-friendly way. A number of current examples of the application of this technology in industries are described in the following.

The electro-pulsed inductive coalescer (EPIC), designed in accordance with electrostatic coalescing principles, uses a pulsed DC field between an insulated central electrode and the earthed metal wall of the coalescer [34]. The dispersion, introduced through a tangentially offset inlet nozzle (shown in Fig. 3), flows upward and spirals around the insulated electrode while under a high voltage DC field. The dispersion receives continuous electric pulses, promoting droplet–droplet coalescence, resulting in increased droplet size distribution in the outlet dispersion. The performance of EPIC also depends on the properties of the dispersion [34]. In recent years, the EPIC has not been widely used.

The Axsia companies, comprising Axsia FSC, Axsia Serck Baker and Axsia Howmar design and supply electrostatic crude oil dehydration and desalting systems for refinery and oilfield operations together with two and three phase separators [75]. They also have desalter/dehydrator units on board of ocean-going vessels, designed to treat crude oil offshore. This mobile system is of great advantage because it can treat crude oil at petroleum drilling platforms offshore. All Axsia electrostatic coalescers operating offshore use AC electric field technology, with applications for

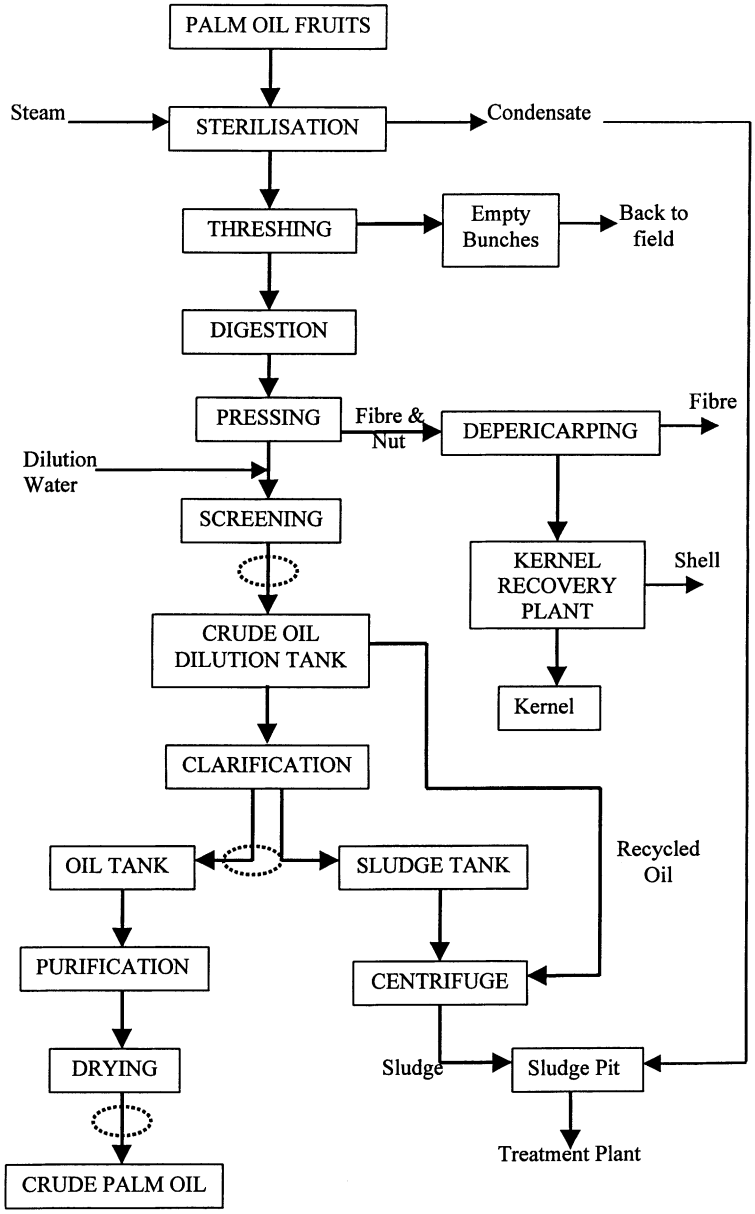

Fig. 6. The conventional process to produce crude palm oil: ⬭ shows the potential application of the electrocoalescence method.

unit capacities up to 350,000 bpd (barrel per day) referring to the range of Axsia desalters supplied world-wide. Typical units used offshore are however less than 100,000 bpd. The 'TriVolt' unit desalter of Axsia Howmar consists of three parallel horizontal electrode grids within the vessel [75].

A major potential application of the electrocoalescence technology is in the edible oil production industry. An example of this is the palm oil processing technology. Conventionally, palm oil can be extracted from treated palm oil fruits and kernel by three different methods, giving rise to different water contents [76–78]. The conventional items of equipment used to separate water from oil are decanters, centrifuges, gravity separators and vacuum dryers. These items of equipment generally have a large residence time and are consequently of considerable dimensions and weight. Fig. 6 shows the schematic diagram of various steps involved in the production of palm oil. The water content affects the quality of the oil as fatty acids can easily form in the oil phase. The separators used here have many disadvantages: they are mechanical, giving a high probability of breakdown. Furthermore, centrifuges are expensive and other devices are very bulky. Moreover, if the oil is not purified and de-watered properly, micro-organisms will survive in the 'dirt' and moisture, producing enzymes and free fatty acids. Thus the content of water in the oil can significantly influence the quality of the oil. The level of moisture content in the oil is usually used as a quality parameter. The moisture content depends on several factors: (a) the effi-

ciency of the de-watering process in the processing plant; (b) the solubility of water in the oil increases with the presence of free fatty acids, especially during storage; (c) the solubility of water in the oil is also affected by the temperature, i.e. increasing with increased temperature. Therefore, the de-watering process is very crucial here, and new efficient technology is highly desirable to be able to process the oil at a much lower temperature without affecting the overall quality. Fig. 6 shows the potential specific areas for this application. The use of electrocoalescers is an attractive alternative for this application.

5. Conclusions

The electrostatic coalescer has proved to be an efficient means of separating water-in-oil type emulsions. Engineering design and better understanding of the mechanisms of droplet–droplet electrocoalescence should lead to the enhancement and development of new types of electrocoalescer. Almost all the electrocoalescers in the oil and petroleum industries use AC electric fields for the separation of water-in-oil emulsions. However, some research work reported in literature indicates some promising performance for pulsed DC electric fields. The existence of an optimum electric field and frequency has been reported, but it has not been widely confirmed [12]. However, it may be intuitively expected that differences in the mechanical and electrical relaxation times of the droplets could give rise to the existence of an optimum voltage and frequency. Further, research is needed to elucidate this issue.

Recent work shows that, under a pulsed DC electric field, chains of water droplets are usually created during periods of high voltage, followed by rapid coalescence during periods of reduced or no voltage. Therefore, a further improvement in the electrostatic coalescence technology with respect to the applied electric field may be achieved by operating the coalescer at an optimum voltage and frequency with reference to the condition of the emulsion, as well as the design of the coalescer itself to give the best electric field configuration.

In a water-in-oil emulsion with a high content of dispersed water, insulating the electrode may be necessary. This is because the high water content tends to produce over-stressing of the electrical coalescer due to a direct conductive path between the electrodes.

A further enhancement can be achieved when the electrostatic coalescer is coupled with a centrifugal force or when employing a multi-stage separator. Moreover, various combinations for emulsion treatment have also been utilised. Besides centrifugal force, heating has also been used with electrical treatment. It has been shown that chemical addition would further enhance electrocoalescence of water droplets in oil emulsions. Other methods that can be combined with electrical treatment are filtration, pressure application and mixing, which enhance the separation efficiency in various ways.

The literature review showed that most of the equipment in the market is big and bulky, having a large inventory of emulsion in the vessel. Therefore, it would be of interest to develop a small portable device, incorporating features such as an optimum applied electric field strength combined with centrifugal force, to further enhance the separation of water droplets present in a water-in-oil emulsion. It should also be possible to install such a device into an existing pipeline without major modifications. Otherwise, disruption for a significant period of time reduces productivity.

In summary, there is a wide scope for developing and inventing new devices for separating dispersed aqueous solutions from oil. This requires an understanding of the fundamental electrocoalescence mechanisms, and of the effects of the electrode design, the dispersion flow direction with respect to the applied electric field, the types of the dispersion and the electric field configuration. In their broader applicability, these new developments and challenges mean that negative impacts to the environment could be significantly reduced, and savings in terms of energy, man-power and time could be greatly enhanced. Moreover, the electrocoalescence technology has potential applications in other industries such as edible oil treatment and bioprocesses.

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