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CHEMICAL AND BIOCHEMICAL PROCESSING*

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USE OF THE ELECTRICALLY-DRIVEN EMULSION PHASE CONTACTOR IN CHEMICAL AND BIOCHEMICAL PROCESSING

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ABSTRACT *An electrically-driven liquid-liquid contactor has been developed to enhance the efficiency of chemical and biochemical processes. A uniform electric field is utilized to induce a drop dispersion-coalescence cycle, producing high surface area for interfacial mass transfer under continuous-countercurrent-flow conditions. The mass-transport capability of this system has been analyzed by observing the extraction of acetic acid from water (dispersed phase) into methyl isobutyl ketone. Results showed that, due to increased efficiency of mass transfer, the electrically-driven device could be an order of magnitude smaller than a conventional contactor accomplishing the same level of separation. In the case of biochemical processes within non-aqueous environments, a biocatalyst (enzymes or bacteria) is introduced in the aqueous (dispersed) phase. The biocatalyst uses nutrients and other reactants to selectively transform species transferred from the continuous (organic) phase to the interior of the drops. An example of such system that has been investigated is the oxidation of p-cresol dissolved in toluene by aqueous-phase horseradish peroxidase.*

INTRODUCTION

One means that is being employed for the development of efficient chemical processes is the application of external fields, such as electric fields, to either enhance existing processes or to provide the basis for new processes. Many electric-field-driven processes are in widespread use, examples of which include electrostatic precipitators, electro dialysis, and electrophoresis¹. This paper is focused upon the emulsion-phase contactor (EPC), a recently developed device that applies electric fields in place of mechanical mixers in liquid-liquid processes, such as solvent extraction.

Solvent extraction is a widespread technology throughout industry, used in processes as varied as the recovery of metals from ores, desalting of crude oil, and purification of antibiotics. The basis of the process is the transfer of chemical species from one liquid to another immiscible liquid. The example of crude oil desalting is perhaps the most easily visualized in order to understand the process. In this case, crude oil containing unwanted amounts of dissolved and suspended salt is placed in contact with clean water. The salt dissolves into the water, and, when the phases are separated, one is left with clean oil in one stream and water containing the salt in the other. A major factor in the success of this process is the means by which the two phases are brought into contact. A process that creates a large amount of surface area between the water and oil will have an increased transfer rate of salt from the oil phase to the water phase. A direct way to achieve a greater amount of surface area is to create smaller drops of one fluid in the other. This is conventionally achieved by mechanical means, such as forcing liquid through nozzles or perforated plates, or by agitation of bulk liquids with stirrers. Generally, greater energy input results in smaller drop sizes and thus faster transport rates. A significant part of the energy input by mechanical means, however, is wasted since it is provided to the bulk fluids in order to effect changes at the interfaces between the fluids.

The application of electric fields to solvent extraction provides the means for significant enhancement in the efficiency of drop breakup. Because the two immiscible fluids in a solvent extraction process are often of greatly differing electrical properties, such as the oil (nonconductive) and water (conductive) of the above example, the application of an electric field results in forces that are concentrated at the interfaces between fluids. If an electric field is applied to an organic liquid

(oil) containing drops of water, the water drops will deform in the direction of the electric field. If the field is sufficiently strong, the water drops will break into many smaller drops. Since the oil is of low conductivity, a device capable of sufficiently high voltage for drop breakup can be designed to have low electrical current requirements and thus low power consumption.

The EPC has been designed to use strong enough electric fields for drop breakup into micrometer-size droplets. In addition, the input electric signal is specially designed to induce drop coalescence. In this way, the drops follow a continuous dispersion-coalescence cycle during their motion from the entrance to the exit of the contactor. The development of the EPC and description of its construction and operation, with test data, are outlined in this paper. In addition, highlights of current industrial applications and the potential impacts of ongoing research developments are discussed.

DEVELOPMENT OF THE EMULSION-PHASE CONTACTOR

Driven by the possibilities presented by the interactions of multiphase liquid systems with electric fields, fundamental research on this topic was conducted at Oak Ridge National Laboratory (ORNL) during the 1980's. Testing of the capability for drop breakup by electric fields indicated that it was possible to create smaller droplets (in the size range of 5 microns) with an energy consumption of less than 1% of conventional means². Voltage requirements for drop breakup were also shown to be lower if the electric fields were applied as pulses with a frequency that closely matched the natural frequencies of the drops. Further testing demonstrated that it was possible to create an emulsion of aqueous droplets in an organic fluid having a large amount of interfacial area and to induce coalescence of the emulsion, forming larger droplets that are suitable for phase separation.

The EPC was invented based upon these concepts. Figure 1 is a schematic diagram of the original EPC test device³. Stainless-steel electrodes were placed near the exit of a stainless-steel nozzle in a conical, 1-L vessel filled with organic liquid. The organic liquid was flowed slowly upward through the vessel while aqueous solution was pumped slowly downward out of the nozzle. During operation, a high-voltage ac or pulsed-dc signal was applied to one electrode while the other was grounded. As aqueous drops flowed out of the nozzle, they were broken up into small droplets by the electric field. It was found that a stable emulsion region could be maintained in the vicinity of the electrodes. Drop coalescence occurred in the lower-field zones near the top and bottom of the emulsion region, leading to good phase disengagement. The larger aqueous drops formed by coalescence at the bottom of the emulsion region fell to the bottom of the vessel for collection, while organic liquid that was essentially free of entrained aqueous droplets flowed from the top.

The potential for enhancement of solvent extraction was tested using the original EPC for a benchmark chemical system of water-acetic acid-methyl isobutyl ketone. Table 1 compares mass transfer performance of the EPC, as measured in terms of the number of theoretical stages per centimeter of column height, to published values for two conventional devices, the York-Scheibel column and the Podbelniak centrifugal contactor.

Table 1. Mass-Transfer Test Results for Original EPC Device

<u>Device</u>	<u>theoretical stages/cm</u>	<u>relative performance</u>
York-Scheibel	0.10	1.0
Podbelniak	0.17	1.7
EPC	1.71	17.1

The results in Table 1 indicated that due to increased efficiency of mass transfer, the active portion of an EPC device could be an order of magnitude smaller than that of a conventional

contactor accomplishing the same level of separation. The potential for capital cost savings is evident, and, since the conventional contactors apply power to the bulk liquid to generate surface area, the decreased volume translates into considerable potential for increased energy efficiency.

Despite the promise of this early EPC testing, further development was necessary to produce a technology that was feasible for industrial application. Of primary concern, throughput rates of the original EPC device were limited; excessive organic flow rate resulted in entrainment of aqueous droplets, while excessive aqueous flow rate resulted in poor mass transfer performance because of increased electrical arcing and coalescence. Further development work was conducted at ORNL to transform this promising concept into a viable technology for industrial application. Design developments included two separate electrode regions and modulated electrical signals. The first of these developments is shown schematically in Figure 2 for a case where the aqueous liquid is more dense than the organic liquid. The upper electrodes in the nozzle region provide high-capacity droplet dispersion from the nozzle, as in the original EPC device, while the lower electrodes form an "operating channel." When the aqueous droplets enter the operating channel, the droplets shuttle back and forth between the oppositely charged electrodes, with further mixing caused by continuous drop coalescence and redispersion. Because they are under the influence of gravity, the droplets have an overall serpentine downward trajectory through the upward-flowing organic phase (Figure 3). For greater phase contact time, a longer operating channel may be employed. This design leads to controlled countercurrent operation, resulting in multistage performance in a single device. Modulated electrical signals, that is, high-voltage pulses of variable duty cycle, allow control of the aqueous dispersion while minimizing electrical arcing.

The improved EPC design was tested in experimental vessels having 30-cm-long operating channels⁴ to evaluate energy consumption, axial dispersion, and mass transport in lab-scale devices. Energy consumption on a volume basis was measured to be 2.4 W/L, which is several orders of magnitude less than that of conventional liquid-liquid contactors. A moderate amount of axial dispersion was measured. Multistage mass transfer was demonstrated in a contactor with a 45-cm electrode height for the system of cupric ion transferring from an aqueous buffer solution to kerosene containing versatic acid. Mass transfer performance of up to four equivalent stages approached the limitations set by the hydrodynamics.

Recent applications of the EPC include the oxidation of p-cresol dissolved in toluene by aqueous-phase horseradish peroxidase⁵ and biodesulfurization of crude oil⁶.

CONCLUSIONS

An electrically-driven liquid-liquid contactor has been developed to enhance the efficiency of multiphase chemical and biochemical processes. This contactor utilizes both non-uniform and uniform electric fields to produce dispersions of fine aqueous droplets in organic media. It is expected that the mass-transfer performance along with the minimal energy requirements of the electrically-driven contactor will make it an attractive possibility for enhanced chemical and biochemical processes.

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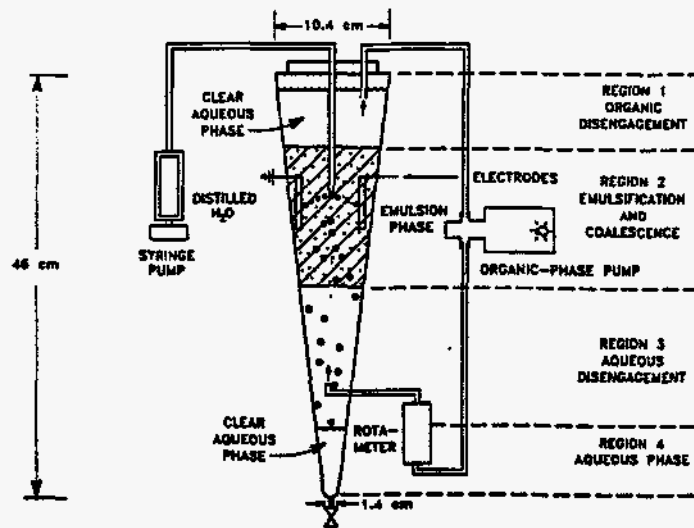


Figure 1. Experimental system for studying an electrically-driven solvent extraction process.

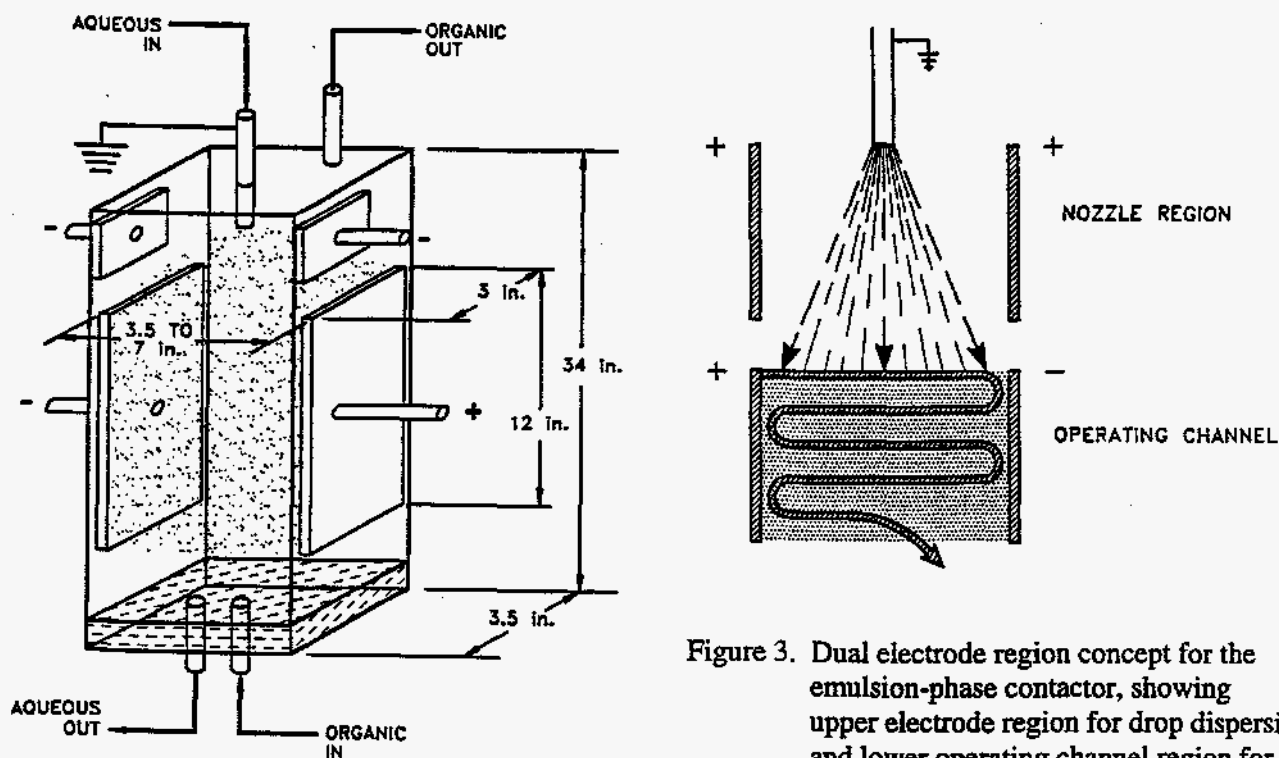


Figure 2. Diagram of experimental emulsion-phase contactor

Figure 3. Dual electrode region concept for the emulsion-phase contactor, showing upper electrode region for drop dispersion and lower operating channel region for phase contacting.