EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY:
Electric field-enhanced extraction & dispersion

TECHNOLOGY CODE: 3.3.1.1

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1. Technology

1.1 Description of technology / working principle

(Feel free to modify/extend the short technology description below)

Liquid-liquid extraction is one of the basic unit operations employed in chemical process industries. The extraction rate is determined by the mass transfer coefficient, the interfacial area and the concentration difference between phases. Since in most cases the diffusivities of liquids are small, usually a significant energy input must be provided to force mass transfer rate to occur at an acceptable rate. In practice, mechanical energy is introduced as extrusion through sieves plates, use of stirrers, rotating discs, or by the use off centrifugal contactors. This represents a very inefficient use of energy because the bulk of continuous phase is manipulated to create the desired effect at the interface.

The ability of superimposed electric fields to improve chemical processes has been well known for many years (Thornton, 1968). The familiar industrial applications range from solid-solid separation in the beneficiation of ores in the mining industry, coalescence of “water-in-oil” emulsions in the petroleum industry, to cleaning of exhaust gases from solid particles in various technologies.

Over the past few decades an extensive effort has been directed to finding new applications of electrical energy in the field mass-transfer operations, mainly solvent extraction (Scott, 1989), as well as dispersion of fluids (liquids and gases) in liquids. The direct utilization of electrical energy offers several advantages, especially in multiphase systems (Ptasinski and Kirchhoff, 1992). These advantages result from the fact that electrical energy supplied to the system interacts selectively with an interface and, to a lesser degree, with the bulk. This interaction may lead to increased rates of heat or mass transfer across the interface. In this aspect the electrical energy is superior to mechanical energy where only a small percentage of the applied energy is actually utilized for the mass transfer enhancement and the majority is dissipated either as heat or a mechanical vibration.

Electric fields are able to improve both factors influencing mass transfer rate: the mass transfer coefficient as well as the interfacial liquid-liquid surface area. The improvement of mass transfer coefficient is mainly obtained by producing a higher degree of fluid turbulence within and around dispersed phase as the result of the interactions between the field and the interface. The main mechanisms promoting interfacial turbulence in the presence of an electric field are:

- higher terminal droplet velocities resulting from electrical forces of attraction exerted on the drops in the direction of motion
- generation of the electrically driven circulating flow in the neighborhood of the interface
- alteration of the velocity profiles within and around individual droplets due to the oscillations by pulsed fields
- interfacial-tension-induced surface flows (Marangoni effects) due to the presence of electric charges (Gneist and Bart, 2003).

Electric fields have the more pronounced effect on the interfacial liquid-liquid surface area what is the second factor influencing the overall mass transfer rate. Generally, surface area generation using electric fields applies the phenomenon of electrostatic spraying or dispersion of one fluid into another, which was discovered in the mideighteenth century by Abbe Nollet (Shin et al., 2004). In recent years, this phenomenon has found important applications in painting, printing, crop spraying in agriculture, among others. The creation of multiphase dispersions in the form of particles, drops, bubbles dispersed in a liquid continuous phase is also very important in many other chemical, biochemical, and environmental processes, such as distillation, stripping, flotation, and oxidation. Two distinctly different electric techniques can be used to create large interfacial surface area in liquid-liquid systems (Figure 1):

- droplet formation in charged nozzles or orifices, as applied in most designs
- direct use of strong electrical stresses to rupture a liquid-liquid interface into extremely small droplets, even small as 5 μm.

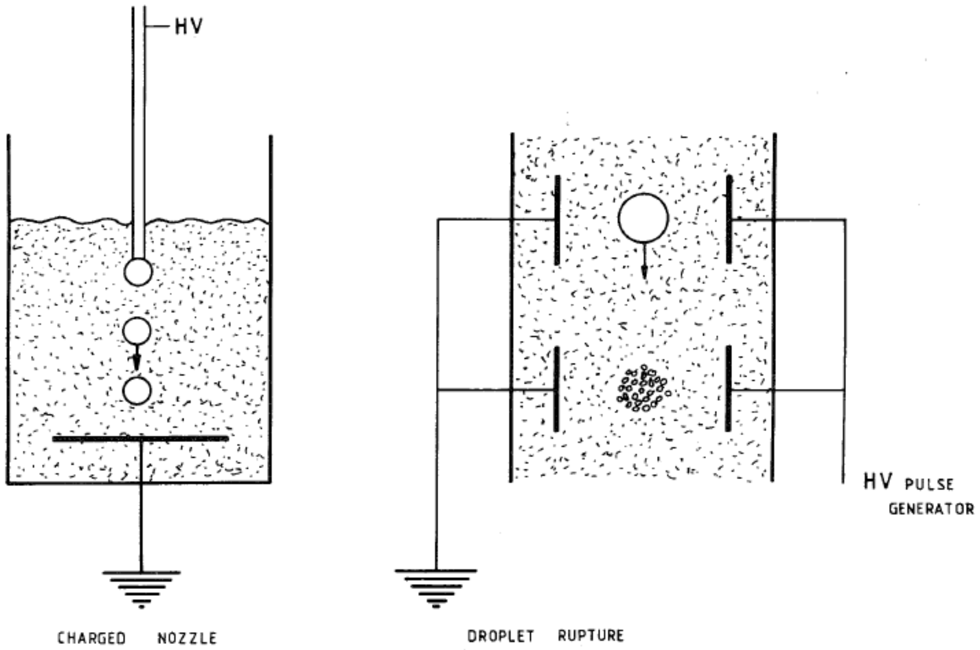

Fig. 1. Surface area generation in an electric field.

Despite many years of study, electrostatic spraying is still not fully understood, due to the complicated nature of this process and to difficulties in theoretical and experimental capabilities. The majority of studies on surface area generation has been devoted to systems composed of electrically conducting droplets in insulating liquids.

1.2 Types and "versions"

(Describe the most important forms/versions of technology under consideration, including their characteristic features, differences and similarities)

The developed continuous flow extraction systems can be broadly classified as (Ptasinski and Kerkhof, 1992):

- charged nozzles or plates devices
- spray columns with vertical electrodes
- emulsion-phase contactors.

The charged plates or nozzles devices (Figure 2) are a modification of the existing sieve-plate extraction columns where the plates also serve as the electrodes (Thornton, 1968). Various electrical potentials of a dc field are applied to the succeeding plates, and this way both droplet formation and mass transfer are controlled by the field.

The second type of electrical contactor (Figure 2) uses a column with long vertically installed electrodes (Kowalski and Ziolkowski, 1981). The nonuniform electric field is obtained by the arrangement of four-pole electrodes with reverse polarity. This configuration creates regions of the weak field where electrical coalescence of the drops takes place as well as regions of the strong field where redispersion of the drops becomes active. The repeated droplet breakage and recombination enables mass transfer to improve in these devices by a factor of 2-5 over the non-filed case.

The most promising is the emulsion-phase contactor EPC developed by the Oak Ridge National Laboratory (Scott and Wham, 1989). This extractor employs transient electric fields such as high-intensity ac or pulsed dc fields, which are very efficient in droplet rupture as shown in Figure 1. The dispersed phase is introduced between vertical electrode pairs where the droplets are ruptured to create a high-surface-area emulsion. A mechanism similar to that of coalescence-redispersion also operates in this case because the coalescence of small droplets follows the rupture steps. The performance of the EPC extractor, when expressed in terms of the number of theoretical transfer stages per centimeter of emulsion height is 1.7 stages/cm compared to the York-Scheibel (0,1 stages/cm) and Podbielniak extractors (0.17 stages/cm).

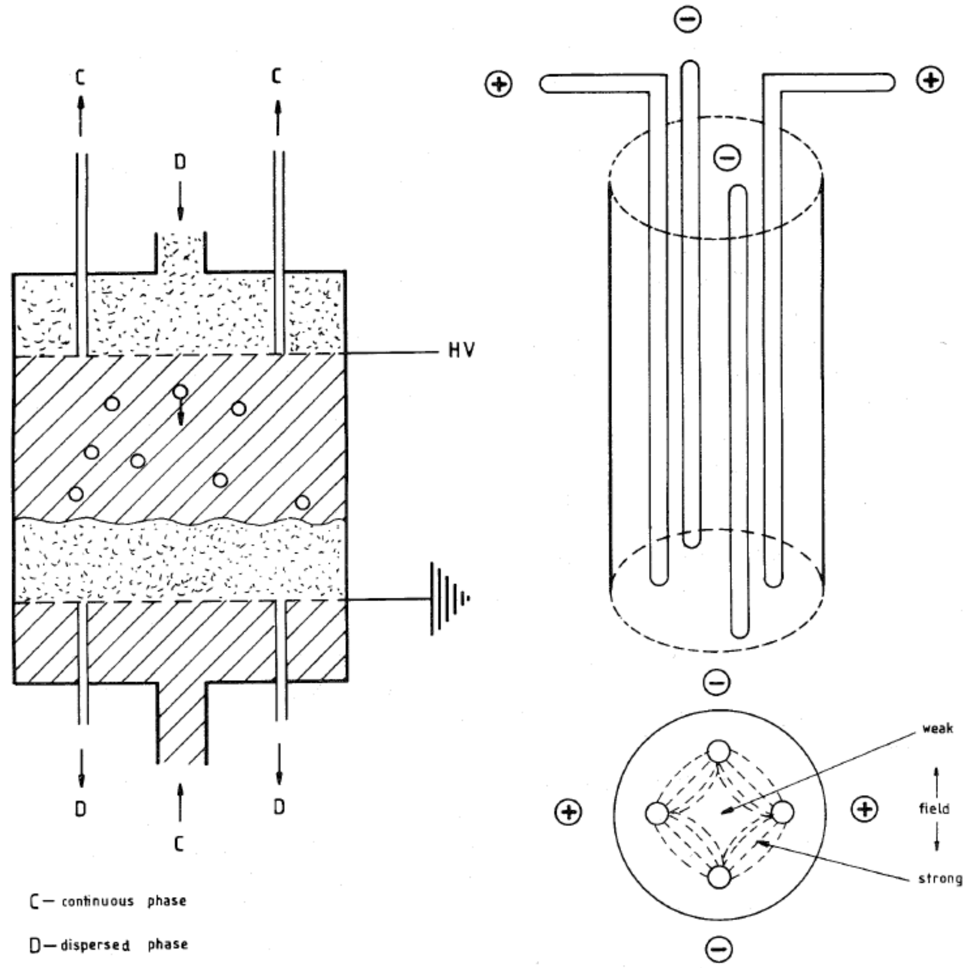

Fig. 2. Schematics of electrical extractors.

Novel developments in this area are an electrostatic pseudo liquid membrane system, ESPLIM, where electric filed is used to extract metals in the fields of hydrometallurgy and wastewater treatment (Reeves et al., 1999) as well as reactive extraction, where liquid ion exchangers LIX are applied (Bart, 2006).

On the other hand the electrically enhanced dispersions can be classified depending on the conductivity of dispersed/continuous phase (Tsouris et al., 1998) as:

- "normal" spraying, that is spraying of a relatively conductive fluid into insulating fluid
- "inverse" spraying, that is spraying a less-conductive fluid into a more-conductive fluid, including gas-liquid dispersions (Sarnobat et al., 2004).

"Normal" spraying is much easier for realization and is applied in industrial applications such as ink-jet printing or fuels spraying. "Inverse" spraying is more difficult than the reverse case and this is due to the high possibility of generating a short-circuit. The "inverse" spraying is thus seldom reported in literature, whereby the electrode arrangement is typically a spraying capillary and grounded ring electrode. This category includes not only dispersions of organic liquids into water, but also fine dispersion of gas bubbles in liquids.

1.3 Potency for Process Intensification: possible benefits

(In Table 1 describe the most important documented and expected benefits offered by the technology under consideration, focusing primarily on energy; CO_2 emission and costs, providing quantitative data, wherever possible. Add other benefits, if needed).

Table 1: Documented and expected benefits resulting from technology application

Benefit	Magnitude	Remarks
Energy savings	Reduction of energy consumption by 2-4 orders of magnitude	Large energy reduction is obtained due to selective interaction of electric fields with an interface: • 2-3 orders of magnitude in extraction systems • 4 orders of magnitude in gas-liquid dispersions compared to stirred tanks. Typically, producing 5 μm droplets when contacting the aqueous and organic phases requires 2.4 W/l by electric fields and it would require 25 kW/l in mechanically stirred reactors.
Reduction CO_2 emissions	Several orders of magnitude	This is due to substantial reduction of energy input.
Cost savings	No data available but it can be significant (>50%)	Cost savings are to due to several effects: • energy savings (see above) • smaller equipment size due to increased mass transfer rate (see below) • solvent saving (see below) • better product quality (see below) • increased product yield and selectivity (see below).
Reduction equipment size	50-200%	More compact equipment results from the substantial increase in mass transfer performance. Typical data on mass transfer enhancement in electric fields compared to the no-field case are: • 2-3.5 in spray column with vertical electrodes • 10-20 in the emulsion phase contactors EPC.
Solvent savings	Several orders of magnitude	Less solvents required due to: • much smaller equipment • increased product yield • reduction of solvent degradation due to radiolysis in extraction of nuclear spent fuel.
Increased product yield and selectivity	No data available	This is due to: • enhancement in mass transfer rates • selectivity control by means of the electric field strength.
Better product quality	No data available	In specific cases. Due to: • shorter residence time what is needed in extraction of unstable products, as in biotechnology • lower and uniform size of produced droplets and subsequently fine solid particles.
Improved safety	No data available	Several effects contribute to the improved safety: • more compact equipment • less solvents needed.

1.4 Stage of development

Some electrically enhanced chemical processes have a relatively long tradition and have been in commercial use for nearly 80 years. The applications, which have the longest history and are still in use, are the beneficiation of ores in the mining industry, electrostatic gas cleaning, electrical emulsion breaking in the petroleum industry, and dielectric heating and drying. Similarly, well-known industrial applications of electrostatic spraying include ink-jet printing, fuel spraying, car painting and deposition of herbicides in agriculture.

On the other hand and despite many advantages, electric field-enhanced extraction is still in the development stage, being mainly limited to laboratory research. At the moment the concept of this technique has been demonstrated in the laboratory scale for several applications, including important areas of bulk and fine chemicals, biotechnology, and mineral processing. There are few industrial applications and the most well known is crude oil desalting in the petroleum industry (Warren et al., 1998). Because of these promising preliminary results, implementation of electric extraction for industrial development represents a task for a near-term research.

2. Applications

2.1 Existing technology (currently used)

(Describe technology (-ies) that are conventionally used to perform the same or similar operations as the PI-technology under consideration)

Extraction equipment may be generally classified into two categories:

- stagewise
- continuous (differential) contactors.

The first category includes mixers-settlers equipment, which can operate in batch fashion or continuously. During one stage of extraction the liquids are contacted in a mixer when equilibrium between phases is approached. Next both phases are separated in a settler. Liquids are usually mixed either during flow or in agitated vessels. Settlers can be either gravitational or enhanced by external forces as centrifugal (cyclones) and electrostatic.

The continuous extractors are usually gravity-operated towers equipped with nozzles (spray towers), various packings (packed towers) and perforated-plates (as sieve plate) towers. The efficiency of column extractors can be improved by the input of mechanical energy in form of rotating stirrers (Rotating Disc Contactor, Oldshue-Rushton Tower, Scheibel Extraction Tower) of pulsation (induced by liquid flow or plates). The contacting and mass transfer between phases can be still improved by centrifugal forces as in Podbielniak extractor. In all these devices mechanical energy is provided as kinetic energy to the bulk liquid, wasting a large fraction by viscous dissipation. As previously explained, the electrical energy in electric-field enhanced extractors interacts selectively with a liquid-liquid interface where it is just directly the most efficiently used.

Traditional dispersion devices make use either of nozzles where liquid droplets or gas bubbles are produced or use mechanical energy to produce dispersions as in stirred contactors.

2.2 Known commercial applications

(Is the technology broadly applied on commercial scale? In which process industry sectors is the technology most often applied: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? What is the estimated number of existing applications? In Table 2 provide the most prominent examples of realized applications and provide their short characteristics)

Table 2. Industrial-scale applications of the Technology (existing and under realization)

Sector	Company - Process/Product name/type	Short characteristic of application	Production capacity/ Plant size	Year of application	Reported effects
Oil refineries	NATCO Group, USA - EDD Electro-Dynamic Desalter	Washing of crude oil with fresh water to remove soluble salts	100,000 bbl/day	1980	• 100% reduction in equipment size • elimination of auxiliary pumps, valves and energy • improvement of salt removal from 80% up to 99.93%
Bulk chemicals	CDTECH, USA – MTBE process CDMTBE / ELECTRO-DYNAMIC™ Contactor	Washing of acetonitrile from the hydrocarbon for MTBE unit pretreatment feed	13000 BPD	1992	• 40% savings in the total installed cost • reduction of stage height by a factor greater than 10 • 50-100% reduction of wastewater volume • reducing ACN levels to 1ppm increases both catalyst life and MTBE production
Analytical Laboratories	ABC Laboratories, USA – ExCell 2000/RALLE process	Rapid, automated, liquid/liquid extraction of contaminants from aqueous samples containing suspended solids	Laboratory scale, 400 ml cell	1992	• reduction of labor, time, and solvent volume requirements for analysis

2.3 Known demonstration projects

(Are there any demonstration projects known related to the technology under consideration? In which process industry sectors are those projects carried out: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? In Table 3 provide the short characteristics of those projects.)

Presently no demonstration project are known in the area of electric field enhanced extraction and dispersion.

Table 3. Demonstration projects related to the technology (existing and under realization)

Sector	Who is carrying out the project	Short characteristic of application investigated, including product name/type	Aimed year of application	Reported effects
				•

2.4 Potential applications discussed in literature

(Provide a short review, including, wherever possible, the types/examples of products that can be manufactured with this technology)

The applications of electric fields to enhance extraction and dispersions discussed in the literature cover a wide range of processes. In numerous papers almost all classical fields of extraction are covered, including chemical, petroleum, food industry, and hydrometallurgy. Recent application relates to upcoming technologies, such as biotechnology and nanotechnology. The majority of applications are demonstrated in the laboratory-scale, including microreactors (Kralj et al., 2005). Below the most important application of electric-field enhanced extraction are indicated divided into industrial sectors:

chemicals

- washing of acetonitrile from the hydrocarbon for MTBE unit pretreatment feed (Schwartz et al., 1992)
- extraction of acetic acid from water by methyl isubutyl ketone (MIBK) – a bench-mark solvent system
- extraction of food dye from water by an organic mixture of versatic acid in kerosene
- removal of methanol from toluene by water
- extraction of benzoic acid from toluene into water
- extraction of furfuraldehyde into n-heptane
- extraction of acetone from n-butyl acetate into water
- extraction of ethanol into n-decanol
- extraction of various chemicals (substituted phenols, beta-chloro ether, esters, chlorinated pesticides, poly nuclear and nitro-aromatics, and alpha-beta unsaturated ketone) from water into methylene chloride
- separation of copper from iron using LIX (liquid ion exchanger)
- extraction of acetic acid from organic phase (xylene or tetrachloride) into water
- extraction of isopropyl alcohol by water from heptane
- reprocessing of high burnup nuclear spent fuel using tri-n-buthyl phosphate

petrochemical industry

- desalting of crude oil
- removal of organic sulfur from petroleum feedstocks

biotechnology

- extraction of penicillin G and other antibiotics from a broth into dichloromethane
- recovering and purifying biochemical products from complex fermentation broth
- recovery of ethanol from fermentation solutions in biomass-to-ethanol process

food industry
- extraction of sugar and pigments from red beets, apples, carrots
- extraction of vegetable oils from maize kernels, olives, and soybeans
- extraction of water-soluble polysaccharides from linseeds

hydrometallurgy
- extraction of copper and nickel from water into Shellsol 2046 as the organic phase
- extraction of copper from water into organic mixture of LIN 65N extractant in ESCAID 100 diluent
- extractive separation of rare earth metals (zinc, praseodymium) from water into an organic phase (ISOPAR M) containing an extractant (D2EHPA)
- extraction of cobalt in a electrostatic pseudo liquid membrane (ESPLIM)

The most important applications of electric fields to create fine dispersions (no mass transfer) are listed below:
- production of high-quality, ultrafine inorganic particles as the key building blocks for diverse advanced structural and functional materials, such as high performance ceramics and alloys (DePaoli et al., 2003,)
- interfacial polymerization reactions
- production of inorganic microspheres and porous microcapsules
- hydrolysis of high oleate sunflower oil by non-specific lipase
- cleaning polluted water by ozone (g-l dispersion)
- dispersion of fine aqueous droplets in supercritical carbon dioxide as an environmentally friendly solvent

3. What are the development and application issues?

3.1 Technology development issues

(In Table 4 list and characterize the essential development issues, both technical and non-technical, of the technology under consideration. Pay also attention to "boundary" issues, such as instrumentation and control equipment, models, etc.) Also, provide your opinion on how and by whom these issues should be addressed)

Table 4. Technology development issues

Issue	Description	How and by whom should be addressed?
Optimization and design of commercial scale equipment	The results up till now indicate the potentialities of electrically augmented extraction and dispersion processes. Existing devices should be optimized to improve hydrodynamic (holdup, backmixing), as well as electrical aspects (reduction of electric potential and efficiency improvement). New designs have to be developed including system and electrode geometry/coatings, nozzle systems for various types of electric fields (ac, dc, pulsed).	R&D projects performed at the universities and research institutes in cooperation with producers of electrical power systems. At universities a much close cooperation between chemical engineering (chemistry) groups from one side and electrical engineering groups from the second, should be promoted.

Development of scale-up and throughput methods	The successful application of electric fields to enhance extraction and dispersion are demonstrated mainly in the laboratory scale. The fundamental problem in further development of large-scale devices is better control of two-phase flow at augmented flow rate. To this end the fundamental analysis of the system geometry as well electrical principles is needed.	R&D projects performed at the universities and research institutes in cooperation with producers of electrical power systems
Models dedicated to mechanism of hydrodynamics and mass transfer in electric fields	In spite of the demonstrated advantages, little is known either on the mechanism of the electrically aided processes or the important parameters of fields or systems responsible for these effects. Fundamental models have to be developed in the area of electrohydrodynamics and mass transfer, which can be used in the further optimization and design work.	R&D projects performed at the universities by the mixed grouped from among chemical and electrical engineering departments
Development of robust power supply systems	New power supply units have to be designed and developed for increased electrical efficiency and possibility of using pulsed fields. The technology should be primarily based on solid state concepts.	R&D projects performed at the universities and research institutes in cooperation with producers of electrical power systems
Control systems for commercial devices	The successful implementation of electrically aided extraction and dispersion depends highly on robust control systems to manage two-phase flow hydrodynamics and electrical behavior of commercial devices. This should include a good matching between physicochemical properties of the system and its electrical characteristics.	R&D projects performed at the universities and research institutes in cooperation with producers of electrical power systems.

3.2 Challenges in developing processes based on the technology

(In Table 5 list and characterize the essential challenges, both technical and non-technical, in developing commercial processes based on the technology under consideration. Also, provide your opinion on how and by whom these challenges should be addressed)

Table 5. Challenges in developing processes based on the technology

Challenge	**Description**	**How and by whom should the challenge be addressed?**
Increase flow rate and the volume fraction of the dispersed aqueous (conductive) phase in extraction and dispersion applications.	A relatively high flow rate prevents the ability of the system to disperse the conductive phase and results in electrical shorting between the electrodes, decreasing system performance and increasing power consumption.	This challenge should be addressed in the R&D projects in the area of design and optimization of commercial scale devices.
Reduce backmixing of the dispersed aqueous phase.	Backmixing of the aqueous phase is due to the end and wall effects of the operating electrodes, This effects negatively influence overall mass transfer performance. The proper geometry of electrodes could improve this problem.	This challenge should be addressed in the R&D projects in the area of design and optimization of commercial scale devices.

Controlling and altering behavior in electric field by surface-active materials	The field strength is usually influenced by the potential difference, electrode configuration and system properties. Adding charged surface-active material to the system, which can be absorbed onto droplet-continuum interface could provide extra means for controlling or altering behavior in electric fields.	This challenge should be addressed in the R&D projects carried out at the universities and research institutes.
Extension of applications to the processes operated in the "conductive-phase-continuous" mode	The present techniques are limited to fluids with appropriate electrical properties, which operate in the "insulating-phase-continuous" mode. A significant portion of the fluid pairs utilized in the industry today operates at the opposite mode that is a "conductive-phase-continuous" mode. In such cases high conductivity of continuous phase prevents the electric field from holding, because the electrical charge leaks through the fluid and causes current and breakdown of the system.	This challenge should be addressed in the R&D projects carried out at the universities and research institutes.
Safety	Electrically augmented devices use the potential difference about few kV what present a potential hazard to peoples. Similarly, induced electric fields can negatively influence the proper action of other electric and electronic devices in the close surroundings. All these effects have to be eliminated by proper design based on electromagnetic compability.	Research groups and manufactures of electrical devices
Social acceptance	The traditional use of electricity in the chemical and process industry is restricted to lighting and electric engines what is an indirect use of electrical energy. Electric-field augmented devices such extractors represent a direct use of electrical energy what is not commonly demonstrated and accepted in these industries. Successful demonstration projects can positively change the current image of direct use of electricity.	Research groups, manufactures of electrical devices, and industrial users

4. Where can information be found?

4.1 Key publications

(Provide the list of key publications in Table 6)

Table 6. Key publications on the technology

Publication	Publication type (research paper/review/ book/report)	Remarks
Bailes PJ, Electrically augmented settlers and coalescers for solvent extraction, 1992, *Hydrometallurgy*, 30, 417-430.	Research paper	Metals extraction, coated electrodes
Bart H-J, 2006, Reactive extraction in electric fields, *Surfactants Science Series*, 130, 465-491.	Review	Reactive extraction
DePaoli DW, Tsouris C, Hu MZ-C, 2003, EHD micromixing reactor for particle synthesis, *Powder Technology*, 135-136, 302-309.	Research paper	L-L dispersions

Gneist G, Bart H-J, 2003, Influence of high-frequency AC fields on mass transfer in solvent extraction, 2003, *J. Electrostatics*, 59, 73-86.	Research paper	Comparison ac – dc fields
Kowalski W, Ziolkowski, 1981, Increase in rate of mass transfer in extraction columns by means of an electric field, *International Chem. Engng*. 21(2), 323-327.	Research paper	Spray column with vertical electrodes
Kralj JG, Schmidt MA, Jensen KF, 2005, Surfactant-enhanced liquid-liquid extraction in microfluidic channels with inline electric-field enhanced coalescence, *Lab on Chip*, 5, 531-535.	Research paper	Microreactors
Ptasinski KJ, Kerkhof PJAM, 1992, Electric field driven separations: phenomena and applications, *Sep. Sci. Technol*. 27 (8&7), 995-1021.	Review	Review on electric-field driven separations
Reeves MJ, Bailey AG, Howard AG, Broan CJ, 1999, Factors influencing operational efficiency of an electrostatic solvent extraction system, *Inst. Phys. Conf. Ser*. 163, 257-226.	Research paper	Extraction in Electrostatic Pseudo Liquid Membrane ESPLIM
Sarnobat SU, Rajput S, Bruns DD, DePaoli DW, Daw CS, Nguen K, 2004, The impact of external electrostatic fields on gas-liquid bubbling dynamics, *Chem. Engng. Science*, 59, 247-258.	Research paper	G-L dispersions
Scott TC, Use of electric fields in solvent extraction: a review and prospectus, 1989, *Sep. Purif. Methods*, 18, 65-109.	Review	First review on electric extraction
Scott TC, Wham RM, An electrically driven multistage countercurrent solvent extraction device: the emulsion-phase contactor, 1989, *Ind. Eng. Chem. Res*. 28, 94-97.	Research paper	Emulsion-phase contactor EPC
Schwartz E, Rock K, Byeseda J, Pehler R, 1992, An improved process for MTBE unit feed pretreatment, 1992, in: First Separations Division Topical Conference on Separation Technologies: New Developments and Opportunities, *AIChE Annual Meeting 1992*, Miami Beach, USA, 236-241.	Conference proceedings	Commercial application
Shin W-T, Yiacoumi S, Tsouris C, 2004, Electric-field effects on interfaces: electrospray and electrocoalescence, *Current Opinion Colloid Interface Science* 9, 249-255.	Research paper	L-L dispersions
Tsouris C, Shin W-T, Yiacoumi, 1998, Pumping, spraying, and mixing of fluids by electric fields, *Canad. J. Chem. Engng*. 76, 589-599.	Research paper	L-L dispersions
Thornton JD, The applications of electrical energy to chemical and physical rate processes, 1968, *Rev. Pure Appl. Chem.* 18, 197-218.	Review	First review paper on electric separations
Warren KW, Sams GW, Nakayama T, 1998, Electrostatic fields: essential tools for desalting, in: *AIChE Spring Meeting 1998*, New Orleans, USA.	Conference proceedings	Commercial application
Wood, TS, et al, 1992, Rapid, automated, liquid/liquid extraction of contaminants from aqueous samples containing suspended solids, 1992, in: First Separations Division Topical Conference on Separation Technologies: New Developments and Opportunities, *AIChE Annual Meeting 1992*, Miami Beach, USA, 231-235.	Conference proceedings	Commercial application

4.2 Relevant patents and patent holders

(Provide the list of relevant patents in Table 7. Under "remarks" provide, where applicable, the names/types of products targeted by the given patent.)

Table 7. Relevant patents

Patent	Patent holder	Remarks, including names/types of products targeted by the patent
US 4606801, JP 62019233, Electrostatic mixer/separator, Prestridge FL, Johnson BC.	Combustion Engineering, Inc., Windsor, Conn.	Crude oil desalting
US 4747921, Liquid/liquid contacting, Bailes, PJ, Stitt EH.	University of Bradford, Bradford, England	Simultaneous electric fields and high shear mixing
US 4767515, Surface area generation and droplet size control in solvent extraction systems utilizing high intensity electric fields, Scott TC, Wham RM.	DOE, Washington, D.C.,USA	Emulsion-phase contactor EPC developed at Oak Ridge National Lab.
US 5384023, Solvent extraction method and apparatus for recovering analytes, Stalling DS et al.	Analytical Bio-Chemistry Laboratories, Inc, Columbia, Mo.	Automated analytical device
US 5385658, Electric field controlled emulsion phase contactor, Scott TC.	Martin Marietta Energy Systems, Oak Ridge, Tenn.	Emulsion-phase contactor EPC developed at Oak Ridge National Lab.
US 5411651, Method for electrostatic liquid/liquid contactor, Yamaguchi M, Kanno M.	National Tank Company, Houston, Tex.	Desalting of crude oil
US 5421972, Process and apparatus for removing soluble contaminants from hydrocarbon streams, Hickey TP, Byeseda JJ.	National Tank Company & Catalytic Distillation Technologies, Pasadena, Tex.	ACN removal from MTBE feed unit
US 5762775, Method for electrically producing dispersions of nonconductive fluid in a conductive medium, DePaoli DW, Tsouris C, Feng JQ.	Lockheed Martin Energy Systems, Oak Ridge, Tenn.	Inverse dispersions
WO 97232633, US6051112, Extraction method and apparatus, Broan CJ, Williams TJ, Bailey AG.	British Nuclear Fuels PLC, United Kingdom	ESPLIM extractor
US 6060029, A process for the extraction of metal, particularly copper, from aqueous ammonical solutions with beta-diketone extractants, Virnig MJ, Fisher GT, Kordosky GA.	Henkel Corporation, Gulph Mills, Pa.	Metal extraction
US 6265025, Method for production of ultrafine particles by electrohydrodynamic micromixing, DePaoli DW, Hu ZC, Tsouris C.	Lockheed Martin Energy Research Corporation, Oak Ridge, Tenn.	Production of monodisperse particles
JP 2005211708-A, Liquid-liquid extraction device, has electric field application mechanism to apply electric field gradient to carry out dielectric migration of solute along surface direction in extracted solution at flow path, Wada Y.	Shimadzu Corporation, Japan	High speed extraction

4.3 Institutes/companies working on the technology

(Provide the list of most important research centers and companies in Table 8)

Table 8. Institutes and companies working on the technology

Institute/Company	Country	Remarks
Oak Ridge National Laboratory, Oak Ridge, (Dr D.W. DePaoli, Dr C. Tsouris)	USA	Research group with the longest experience in extraction and dispersion systems
Technical University of Kaiserslautern (Prof. H-J. Bart)	Germany	Electrostatic extraction and dispersion
Parker Cooperative Research Centre, Perth, (Prof. M.K. Briggs)	Australia	Applications in hydrometallurgy
NATCO Group, Houston, (Dr K.W. Warren)	USA	Development of crude oil desalters
Ben-Gourion University of Nagev, (Prof. T. Elperin)	Israel	Fundamental studies on mass transfer in electric fields
Purdue University, Prof. O. Basaran	USA	Electrohydrodynamics
Massachusetts University of Technology, (Prof. K.F. Jensen)	USA	Electric field enhancement in microreactors
Eindhoven University of Technology (Dr G. Pemen)	The Netherlands	Gas-liquid dispersions
University of Bradford, Prof. P.J. Bailes	United Kingdom	Extraction systems
University of Canterbury, (Prof. L.R. Weatherley)	New Zealand	Electrically enhanced extraction

5. Stakeholders

5.1 Suppliers and developers

(Provide the list of key suppliers/developers in Table 9)

In general there are no suppliers of commercial-scale devices for electric-field enhanced extraction or dispersion. There is only one supplier of electric-filed desalters for crude oil. The manufacturers of other electrically augmented devices, such as electrostatic precipitators or coalescers, as well producers of power systems, can be seen as potential stakeholders.

Table 9. Supplier and developers

Institute/Company	Country	Remarks
NATCO Group	USA	Supplier of electrically augmented crude oil desalters
Siemens	Germany	One of the largest manufacturers of electrostatic precipitators
Babcock & Wilcocks	USA	One of the largest manufacturers of electrostatic precipitators

Alstom	France	One of the largest manufacturers of electrostatic precipitators
Turbosonic Technologies	USA	Manufacturer of air pollution systems including electrostatic precipitators
Mitsubishi Heavy Industries	Japan	Manufacturer of electrostatic precipitators
Cottrell	Korea	One of the largest manufacturers of electrostatic precipitators
Neundorfer	Germany	Manufacturer of electrostatic precipitators
Alden	USA	Manufacturer of electrostatic precipitators
IPPC Industries	USA	Manufacturer of electrostatic precipitators
NWL Transformers	USA	Manufacturer power systems products for the industry
Delta Electronics	USA	Manufacturer power supplies systems for the industry
Imtech	The Netherlands	Technical service provider in the field of electrical engineering
Vision Dynamics	The Netherlands	Developer of powers systems

5.2 End users

(Describe the existing and potential end-users, other than those already listed in Table 2)

The potential end users are companies operating in various branches of chemical and process industries, particularly,

- oil refineries
- bulk and fine chemicals
- food and agriculture industry
- biotechnology
- hydrometallurgical industry

Moreover, additional end users can be considered in the fields of wastewater treatment and analytical laboratories for chemical and biochemical products (Woods et al., 1992).

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

The advantages of electrical-field enhanced extraction and dispersion result from the fact that electrical energy supplied to the multiphase-system interacts selectively with an interface and, to a lesser degree with the bulk. These technologies are able to reduce energy consumption by 2-4 orders of magnitude and enhance the mass transfer rates by a factor of 2-20 compared to the no-field cases. Currently, the majority of applications concerns the laboratory-scale, but there are already some commercial applications, mainly in the petrochemical industry as well as analytical laboratories. In the next future more industrial application can be realized, particularly in chemical, biochemical, food, and hydrometallurgical industries. To this end more development work is needed, mainly in the area of scale-up as well as eliminating "social acceptance" barriers in the industry concerning the direct use of electrical energy.