CONF-9707109--1

STATUS AND DIRECTIONS IN ELECTROSEPARATIONS

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Presented at the
Electric Power Research Institute (EPRI)
July 21, 1997

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Status and Directions in Electroseparations

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"Electroseparations" has been defined as "the use of electricity or electromagnetic fields to produce and enhance chemical or physical separation" (Byers and Amarnath, 1995). Historically, electroseparations have been identified with such technologies as laboratory-scale electrophoresis, which is a powerful technique for the analysis and characterization of complex biological mixtures, electrolytic applications, in which chlor-alkali and aluminum industries account for 3 to 5 percent of the total power usage in the United States, and electrostatic precipitators which are used for the removal of particulates from gaseous emissions from furnaces and power plants. In addition to these traditional applications, many new technologies are at various stages of development and are expected to have a major impact on various industries in the future. Some examples of these technologies are electrodialysis, radiant processing (UV/infrared, microwave, and radio-frequency heating), electrochemical membrane processes, electrokinetic remediation, magnetic separations, electrosorption, electrically assisted dewatering, electrically driven solvent extraction, electrically assisted distillation, and dielectric filtration (Williams and Byers, 1994; Muralidhara, 1994; Qutubuddin et al., 1996). The use of such electrically driven technologies provides several potential advantages including (i) the widespread availability of electricity, (ii) its absence of an inventory requirement, (iii) the established safe handling techniques associated with the use of electricity, (iv) significant increases in efficiency, and (v) unique capabilities that make completely new means of separations possible.

In terms of the underlying phenomenon responsible for separation, electroseparations are classified as: (i) current-carrying processes, (ii) fields-driven processes, and (iii) transport enhancement by external fields. For current-carrying processes, such as electrically driven membranes or electroremediation, a definite circuit is established within the media containing the species to be separated and the current corresponds to motion of the separating species. Fields-driven processes, such as magnetic separations, are characterized by high-field-strength applications that develop selective interactions between the field and the separating species that provide the driving force for separation. Electromagnetic fields may be used to enhance heat or mass transport by increasing mixing and generating interfacial area between phases.

In this presentation, a summary of research conducted in the area of electroseparations at the Chemical Technology Division of Oak Ridge National Laboratory is presented. Fields-driven processes, including (i) phase equilibria modification by electric fields and (ii) magnetically seeded separations, as well as transport-enhancement processes by electric fields, including (i) surface area generation and (ii) electroconvection, are discussed. It is shown that electric fields can change the concentration of the vapor phase during the distillation of a binary mixture, which may have applications in separations by distillation that consume significant amounts of energy. It is also shown that ddition of colloidal seed particles of high magnetic susceptibility to a suspension of non-magnetic particles and subsequent flocculation between seed and non-magnetic particles form paramagnetic flocs that can be removed by high-gradient magnetic filtration. Inverse electrostatic spraying, which is the spraying of a non-conductive fluid (such as air) into a conductive fluid (such as water), is introduced and compared with normal electrostatic spraying, which is the spraying of conductive fluid into a non-conductive fluid. Applications of normal electrostatic spraying, including the development of a bioreactor for oil desulfurization, and inverse electrostatic spraying, including ozonation of an aqueous system, are discussed. It is also shown that electroconvection, caused by electric fields, may result in simultaneous pumping, spraying, and mixing of fluids.

In summary, new phenomena caused by electric fields are introduced and their potential applications in electroseparations are discussed.

Acknowledgments
The work discussed in this presentation is funded by the Environmental Management Science Program, the Efficient Separations and Processing Crosscutting Program, and the Division of Chemical Sciences, Office of Basic Energy Sciences, of the U.S. Department of Energy, under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp. Additional funding for applied research in electro-distillation and electro-ozonation is provided by the Electric Power Research Institute.

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Introduction to Electroseparations

- "Electroseparations" is the use of electricity or electromagnetic fields to produce and enhance chemical or physical separation (Byers and Amarnath, 1995).
- Historically, electroseparations have been identified with:
  - Electrophoresis (analysis and characterization of complex biological mixtures)
  - Electrolytic applications (aluminum industries account 3 to 5 percent of the power usage in the U.S.)
  - Electrostatic precipitators (removal of particulates from gaseous emissions from furnaces and power plants)
- Many new technologies are at various stages of development.

Emerging Electroseparations Technologies

- Electrodialysis
- Radiant processing (UV/IR, microwave, radio-frequency, sound)
- Electrochemical membrane processes
- Electrokinetic remediation
- Magnetic separations
- Electrosorption
- Electrically assisted dewatering
- Electrically driven solvent extraction
- Dielectric filtration

(Williams and Byers, 1994; Muralidhara, 1994)

Classification of Electroseparations Processes Based on the Underlying Phenomena

- Current-carrying processes
  - electrolysis
  - electrochemical membrane processes
- Fields-driven processes
  - electrophoresis
  - magnetic separations
- Transport enhancement by external fields
  - electric field-enhanced surface area generation
  - electric field-driven convection

Fields-Driven Electroseparations Currently Studied at Oak Ridge National Laboratory

- Modification of phase equilibria by electric fields
  - Environmental Management Science Program (DOE)
  - EPRI
- Magnetically seeded separations
  - Efficient Separations and Processing Crosscutting Program, Office of Science and Technology, Office of Environmental Management (DOE)

Phase Equilibria Modification by Electric Fields: Background

- Electric fields have been known to enhance
  - Heat transfer in boiling and condensation
  - Mass transfer in liquid-liquid extraction
- Effect of electric fields on the boiling point of a liquid have been reported
  - Experiments showed contradictory results
  - Theoretical calculations point to no change
- Molecular simulations on dipolar fluids show
  - electric fields change the VL phase envelope

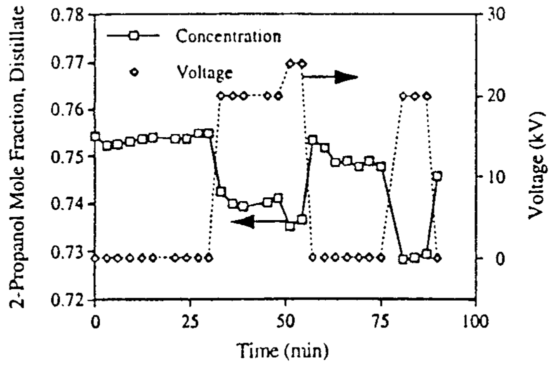
Phase Equilibria Modification by Electric Fields: Objectives

- Modify phase equilibria using electric fields
  - Vapor Liquid Equilibria (VLE)
  - Liquid Liquid Equilibria (LLE)
  - Solid Liquid (SLE) and Solid Vapor (SVE) Equilibria
- Understand the mechanism
- Investigate practical applications

Distillation

- Most popular separation process
- The US chemical industry spends 2 Quad Btu per year on distillation
- Limitations to separation by distillation include
  - mass transfer/heat transfer (tray efficiencies)
  - vapor liquid equilibria
- Experiments in our laboratories showed that electric fields can be used to modify VLE

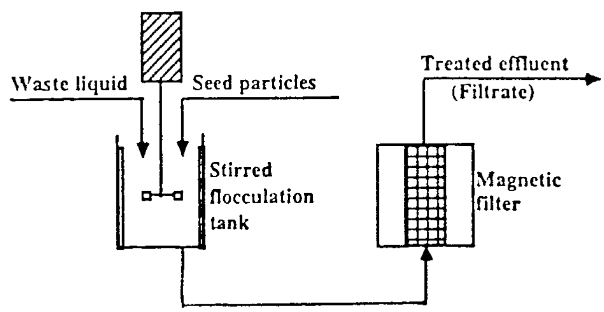
2-Propanol-Toluene Batch Distillation



Ongoing and Future Work on Phase Equilibria Modification by Electric Fields

- Identify systems suitable for electro-distillation
  - VLE
  - Batch
- Effect of electric field on vapor pressure of liquids
- Understand the mechanism
  - FTIR, Raman spectroscopy
  - Dielectric spectroscopy
- Explore liquid-liquid systems

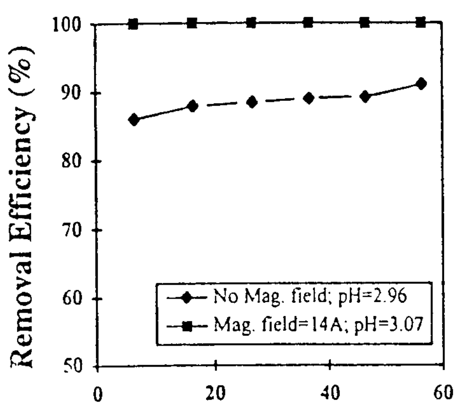
Magnetically Seeded Separations



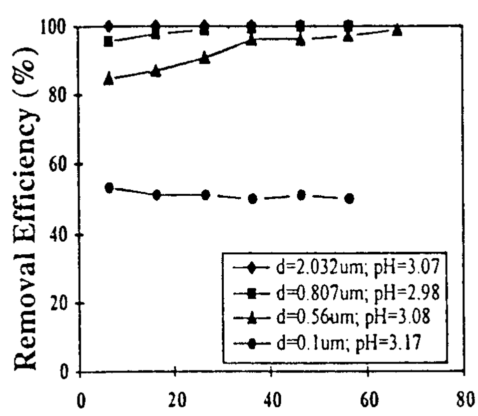
- Colloidal seed particles of high magnetic susceptibility are introduced to a particle suspension
- Seed particles flocculate with para- and/or dia-magnetic particles
- Resulting paramagnetic flocs are removed by a high-gradient magnetic filter

Experiments of Magnetic Filtration

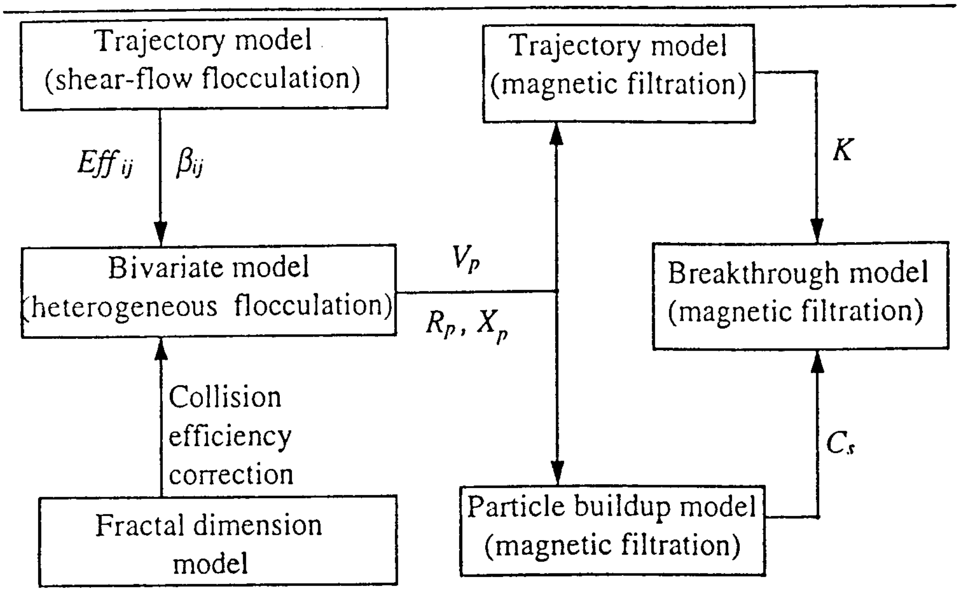
Effect of Magnetic Field on Removal Efficiency



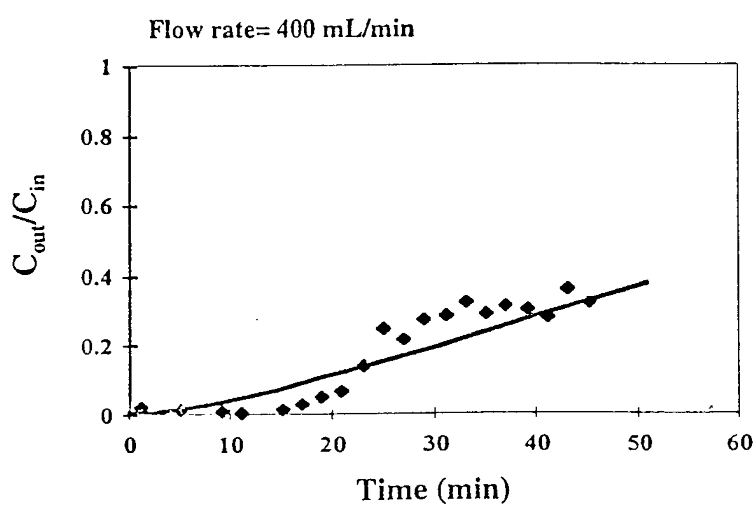
Effect of Particle Size on Removal Efficiency



Schematic of Modeling Work



Comparison of Model and Experiments



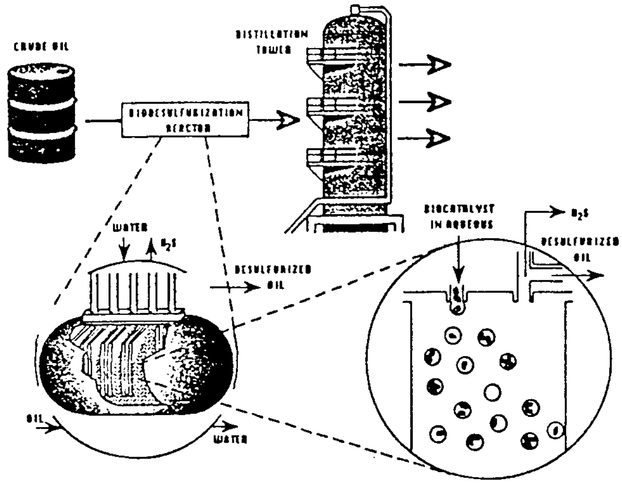
Summary of Magnetically Seeded Separations

- Mathematical models, including a trajectory analysis for shear-flow flocculation, a bivariate population balance model for heterogeneous flocculation, a trajectory analysis of a single magnetic collector, a particle buildup model, and a breakthrough model, have been developed for predicting the performance of a magnetically seeded flocculation and filtration process.
- The model predicts particle breakthrough from a magnetic filter without fitting parameters.
- The model can be used to design magnetic separation processes without using experimental data.

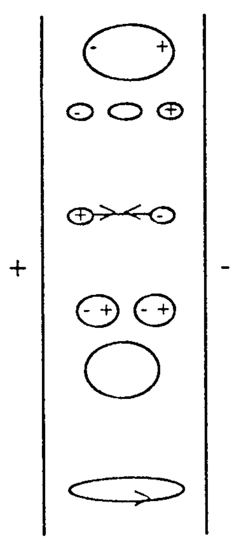
Transport Enhancement by Electric Fields

- Electric-field driven bioreactor for oil desulfurization
  - CRADA between ORNL, Energy Biosystems, Exxon, Unocal, Texaco, Chevron, and Baker Performance Chemicals
- Electrostatic spraying for surface area generation
  - BES, EMSP (DOE)
- Electrostatic ozonation
  - EPRI
- Pumping, spraying, and mixing of fluids by electric fields
  - BES, EMSP (DOE)

Electrically Driven Bioreactor for Oil Desulfurization



Drop Phenomena Occurring in the Bioreactor



- Drop polarization
- Drop breakup
  - formation of charged droplets
- Drop motion and collision due to electrophoresis
- Drop collision and coalescence due to the attractive force between polarized droplets approaching each other
- Enhanced drop collisions due to Coulombic convection

Desulfurization Results Using the Electrically Driven Bioreactor- Comparison with a Batch Stirred Reactor

- Successful emulsion formation and coalescence
- Higher surface area and lower utilization of biocatalyst
- Decreased energy requirement
- Equal oxidation activity as the batch reactor
  - reaction-limited process
  - more active biocatalyst is needed
- No detrimental effect on cell viability or activity has been observed

Transport Enhancement by Electric Fields: Electrostatic Spraying for Surface Area Generation

Normal Electrostatic Spraying

- Electrostatic spraying of conductive fluids, such as water, into nonconductive fluids, such as air or oil, has been extensively used in industrial applications including:
  - —ink jet printing,
  - —paint and crop spraying,
  - —particle manufacturing,

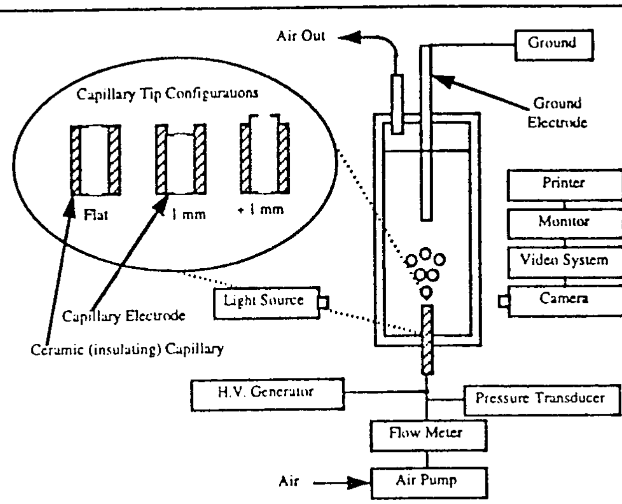
Inverse Electrostatic Spraying (Sato et al., 1993; Tsouris et al., 1994)

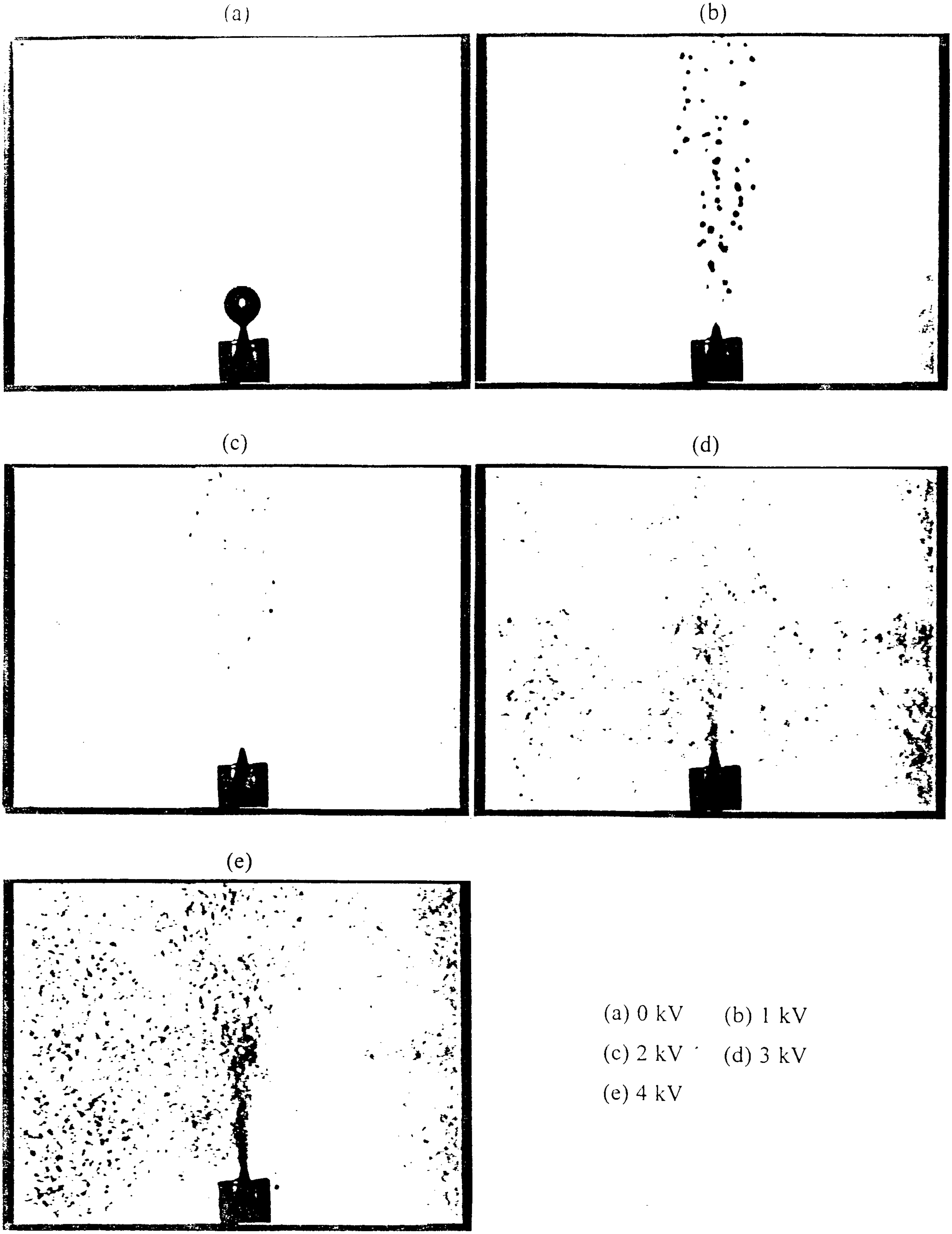
- Electrostatic spraying of nonconductive fluids into conductive fluids may have applications in:
  - —energy-efficient separations,
  - —environmental remediation and biological processes
    - Ozonation, flotation, oxygenation

Formation of Microbubbles by Electric Fields: Motivation

- Many environmental systems use bubbles as reaction media
- Microbubbles have longer residence time, thus higher contact time, and higher surface area for mass transfer
- Electrostatic spraying can be used for the formation of microbubbles
- Possible enhancement of process efficiency by microbubbles

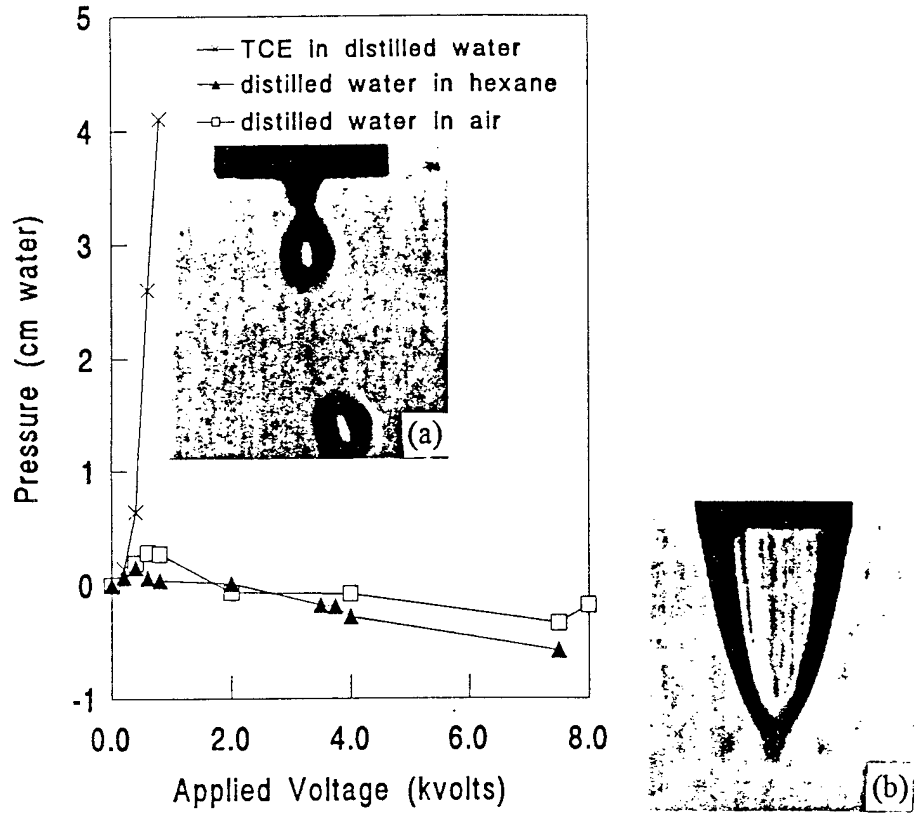
Experimental Assembly

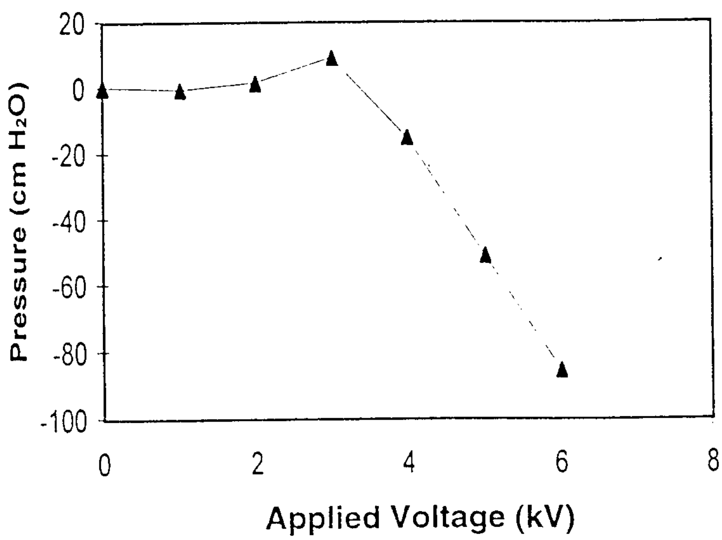




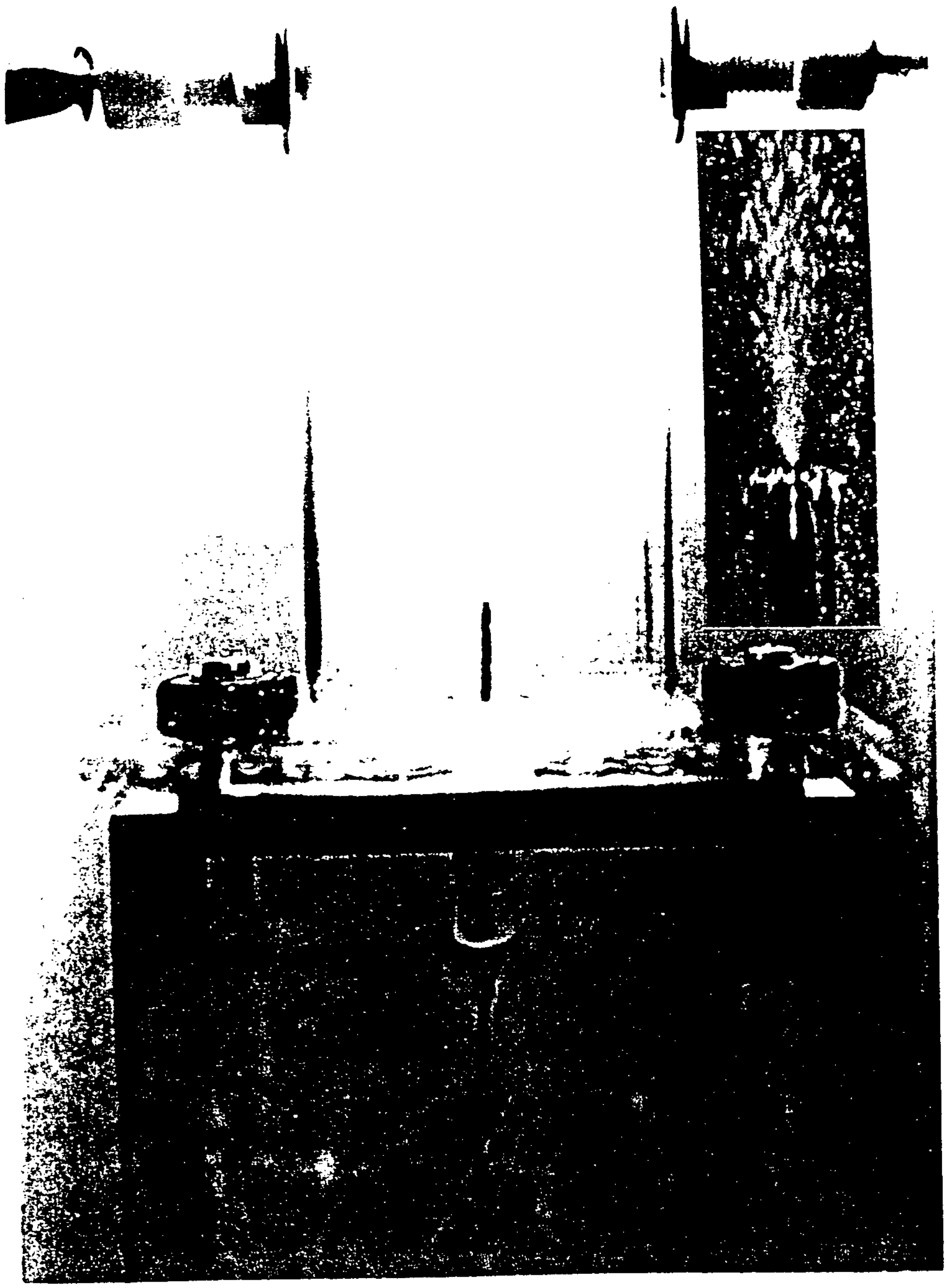
(a) 0 kV (b) 1 kV
(c) 2 kV (d) 3 kV
(e) 4 kV

Comparison of Normal and Inverse Electrostatic Spraying





Pumping and Spraying of Air in Water by Electric Fields



Summary of Microbubble Formation by Electric Fields

- Inverse Electrostatic Spraying of gases and liquids has been demonstrated.
- Three modes of bubble formation under electric fields have been identified.
- Electrohydrodynamic flow causes pumping and mixing of fluids.
- Electric fields may be used for simultaneous spraying, mixing, and pumping of fluids.
- Velocities higher than 1 m/s, generated by electric fields, have been measured.
- The bubble size produced by electrostatic spraying is comparable to the size produced by electroflotation and dissolved air flotation.

Directions in Electroseparations Based on Research at ORNL

- Basic studies of field effects on molecules
  - transport
  - thermodynamic equilibria
- Enhancement of field effects by introducing additional components
  - magnetic seeding to enhance separation of particles
  - ionic seeding to enhance electro-convection
- Basic studies on pumping, spraying, and mixing of fluids by electric fields

Acknowledgments

- C. Byers, V. Shah, D. DePaoli, X. Zhang, M. Spurrier, M. Chattin, K. Blankenship, E. Kaufman
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- S. Yiacoumi
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- BES, EMSP, ESP (DOE)
- EPRI

M97009356

DOE

(18) DOE, XF
(19) UC-900, DOE

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