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DIELECTROPHORETIC FILTRATION AND SEPARATION: GENERAL OUTLOOK

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INTRODUCTION

Electric and magnetic separation have been in use for many years in the mineral and chemical industries. The development of new technologies[1] in the field of magnetic separation, such as magnetohydrostatic separation (MHS), high-gradient magnetic separation (HGMS), wet high-intensity magnetic separation (WHIMS), and magnetic filtration (MF), has generated increasing interest in the behavior of similar methods such as wet dielectric separation[2-4], dielectrophoretic levitation and fractionation[5], and dielectric filtration[6-7] - all using non-uniform electric fields and polarization. In all these cases dielectric particles in a heterogeneous electric or magnetic field are subjected to the action of ponderomotive (gradient) forces.

Few of the mineral beneficiation techniques are applicable to the separation of fine particulates. Certain mixtures can be separated by exploiting specific differences - the dielectrophoretic method, for example, uses the difference in dielectric constants as the main parameter. It is possible, by the introduction of certain materials (e.g. via adsorption) to change the dielectric characteristics and thereby create the conditions needed for separating loose particles, which would not otherwise be accomplished.

In this paper a new separation method is presented, by which mixtures of uncharged particulate and granular solids, having large differences in the dielectric constants of their constituents, can be efficiently separated by means of non-uniform electric fields (of a few kilovolts per cm). Insulating as well as conducting materials can be separated by both HGES and DF. Possible applications of dielectric separation and dielectric filtration techniques are reviewed with regard to the beneficiation of fine-particle feeds, due attention being paid to the different forces and media available.

GENERAL BACKGROUND

A high-tension, high-gradient electrical analogue of the matrix-type magnetic separator (HGMS) and the dielectric filter was developed and tested[6-8]. By replacing the magnetic field of a WHIMS or HGMS by an electric field, and the magnetic matrix elements by dielectric ones, it should be possible to separate minerals having different dielectric constants one from the other. To give an example[7], the matrix elements of a dielectric separator could be glass spheres having a relative dielectric constant of $\varepsilon = 4{,}5$, while copper wires (dielectric constant: infinity) would induce slightly greater electrical forces. The dielectric constant of the separating liquid should lie between those of the minerals to be separated. A suitable liquid may consist of mixtures of carbon tetrachloride (CCl_4) and dichloromethane (CH_2Cl_2), having dielectric constants in the range 2,2 to 9. The mineral with the higher dielectric constant will adhere to the matrix, while the mineral with the lower dielectric constant will pass through it. After the electric field has been removed, the mineral with the higher dielectric constant is washed off to complete the selective separation. Tests carried out on a mixture of 74μ quartz ($\varepsilon = 4{,}0 \div 4{,}5$), and ilmenite ($\varepsilon = 33$) in a mixture of equal volume fractions of CCl_4 and CH_2Cl_2 ($\varepsilon = 5{,}0$), and using 0,1mm diameter copper wires for the matrix, gave +90% recovery for ilmenite and 14% for quartz at 7,0KV/cm field strength. The electrodes in the separator are insulated in order to prevent conduction, so that feed moisture does not cause problems.

Generally speaking, dielectric separation is suitable for: (i) cleaning conducting and non-conducting liquids of dielectric impurities; (ii) separating minerals in S-S-L or S-L systems, e.g. effecting the concentration of finely divided cassiterite or removing precious metal grains from sands; (iii) upgrading precious metal concentrates; and (iv) purifying oils and a variety of high polymers.

Table I shows the conditions necessary for phase separation, either the fractionation of various multi-component and poly-disperse systems, or the fine purification of liquids by the removal of dispersed particles.

Figure 1 shows a laboratory set-up for the fractionation of solids and the filtration of liquids by the HGES and DF techniques.

The amenability of ores, mixtures, suspensions and airborne particles, to processes of separation, upgrading, and cleaning, by means of an electric field depends on the following variables which may be expected to play an important role:

(a) Characteristics of the Material Involved

- size and shape of particles
- dielectric constant of particles relative to that of the liquid medium
- electric conductivity of particles
- degree of liberation
- specific gravity
- chemical stability
- conductivity conditions and viscosity of the suspension

TABLE I: Conditions for phase separation by HGES or DF

	Phase Separation	ε Conditions
Gas purification	S - G	$\varepsilon_S > \varepsilon_G$
Fine purification of liquids	S - L	$\varepsilon_S > \varepsilon_L$
Fractionation of a binary mixture	S - S	$\varepsilon_{S_2} > \varepsilon_L > \varepsilon_{S_1}$

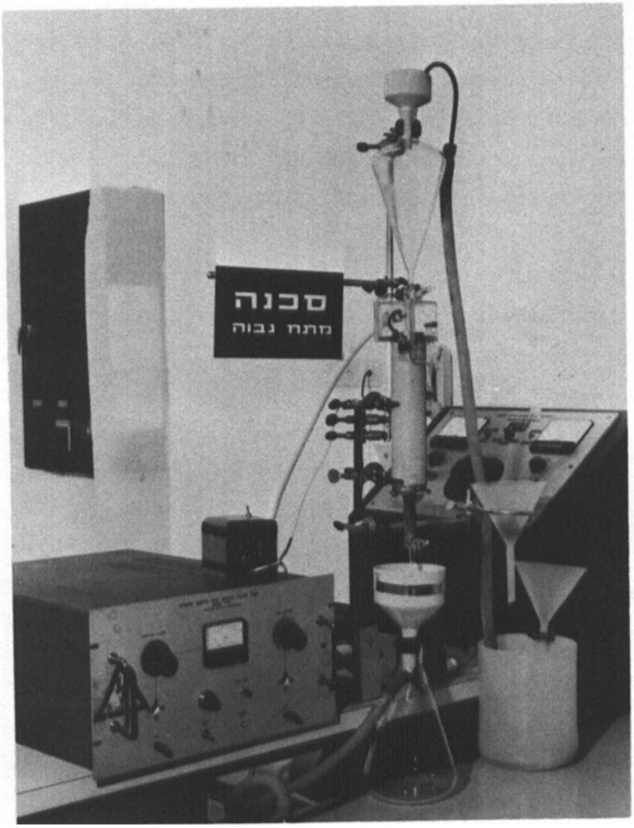

FIGURE 1

HGES and DF laboratory set-up.

(b) Type of Forces Involved

- dielectric force
- drag force
- gravitational force

(c) Characteristics of the Separation System

- electric field data (frequency, voltage, gradient, intensity)
- relative direction of electric gradient
- profile and space geometry of electrodes

- separation cell geometry and working space
- matrix design (size, composition, porosity, thickness)

(d) Operational Parameters

- range of electric field
- type of liquid medium
- particle size range and concentration (solid content)
- static or batch separation process
- continuous separation
- suspension flow rate (residence time of particles)

There are several competing forces that act on a given particle in the separation system: dielectrophoretic, electric, gravitational, and drag forces, the last-named resulting from the relative motion of fluid and particles.

The dielectrophoretic force acting on a non-conducting, small, polarized but uncharged, spherical body at equilibrium, immersed in an insulating dielectric fluid and in a slightly non-uniform electric field, has been shown to be given by[9]:

$$F_E = (\mu \cdot \nabla)E \ , \qquad (1)$$

where μ is the dipole moment vector (induced or permanent), and E the external applied electric field. If the uncharged body is homogeneously, linearly and isotropically polarizable, then,

$$\mu = \alpha V E \ , \qquad (2)$$

where α is the polarizability, and V is the volume of the body. Combining (1) and (2) yields:

$$F_E = \alpha V (E \cdot \nabla) E = \frac{1}{2} \alpha V \vec{\nabla}(E^2) \quad . \qquad (3)$$

For spheres, α is given by:

$$\alpha = 3\varepsilon_1 (\varepsilon_2 - \varepsilon_1)/(\varepsilon_2 + 2\varepsilon_1) \quad . \qquad (4)$$

Eq. (4) is valid only for a dilute suspension. For an extension to higher concentrations see elsewhere[4,10]. From eq. (3), with $V = \frac{4}{3}\pi r^3$, the translational force is given by:

$$F_E = 2\pi r^3 \frac{\varepsilon_1(\varepsilon_2 - \varepsilon_1)}{\varepsilon_2 + 2\varepsilon_1} \vec{\nabla}(E^2) \quad , \qquad (5)$$

where r is the radius of the sphere, ε_1 and ε_2 are the absolute electric permittivities of, respectively, the non-conducting fluid medium and the particle, and $\vec{\nabla}(E^2)$ is the gradient that would be obtained at the specific location of the particles if the particles were not there. The force, F_E, depends on the gradient of the square of the field strength and is therefore independent of electrode polarity and does not change direction under the influence of an ac field. F_E is also dependent on the volume of the particle and on the nature of the internal polarization.

At this point the authors would like to mention an interesting investigation regarding eq. (5), reported in the studies of Kirko et al.[11]. They examined the dielectrophoretic motion of gas bubbles in conditions of weightlessness (in a satellite). Their observations, made in a V-shaped condenser, confirmed the validity of eq. (5).

The difference between the permittivities of particle and medium, $\Delta\varepsilon$, determines both the direction and the magnitude of the force, or the attraction/repulsion of particles. When $\Delta\varepsilon = \varepsilon_S - \varepsilon_L > 0$, the particle will be attracted towards the region of maximum electric field strength. Likewise, when $\Delta\varepsilon < 0$, a particle will be repelled into a zone of low field strength. Note that the dielectrophoretic force, F_E, becomes zero when the particle is suspended in a medium of equivalent permittivity, $\varepsilon_2 = \varepsilon_1$ in eq. (5).

The dielectric force, F_E, is usually determined by the filament size and shape, and by the strength of the electrizing field as seen by the matrix and the particles.

If $\varepsilon_2 \gg \varepsilon_1$ or $\varepsilon_2 \ll \varepsilon_L$, the dielectric force is independent of the dielectric constant of the particle, but its direction is different in the two cases.

If the particle is metallic, $\varepsilon_2 \to \infty$, and since the resistivity of the fluid is supposed to be very high, we obtain

$$F_E = 2\pi r^3 \varepsilon_1 \vec{\nabla}(E^2) \quad . \tag{6}$$

Thus, for a metallic particle, it is impossible to reverse the direction of the force. The particle will always move towards the direction of the largest fields.

For a particle of mass density, ρ_2 immersed in a fluid of density, ρ_1, the net gravitational force is given by

$$F_G = \frac{4}{3}\pi r^3 (\rho_2-\rho_1)\vec{g} \quad , \qquad (7)$$

where $\vec{g}$ is the acceleration of gravity. This force is tiny for small particles but is significant for larger ones.

The magnitude of the drag or viscous force encountered in this system will be as predicted by Stoke's equation:

$$F_D = 6\pi\eta v_r r \quad , \qquad (8)$$

where η is the fluid viscosity, v_r the relative velocity between the fluid and the particle, and r the radius of the particle (assumed to be spherical).

ε_1 in eq. (5), and η in eq. (8), are parameters related to the particular fluid medium. Benzene, kerosene, toluene and other non-conducting liquids having a low dielectric constant and low viscosity may be useful media.

The magnitude of the drag force determines the terminal velocity of the particles. The hydraulic force, F_D, which tends to strip a matrix filament of the particles adhering to it, is basically determined by the velocity of the fluid medium carrying the particles (the higher the velocity, the greater the stripping force).

The net force acting on a particle defines its trajectory, hence the equation for the motion of a small spherical body (for vanishing particle Reynolds numbers) in a dielectric fluid can be approximated as

$$\frac{d}{dt}\text{ (mass x acceleration)} = \sum \text{ (various forces acting on particle)}$$

$$F_{net} = \frac{4}{3}\pi r^3 \rho_S \frac{dv}{dt} = F_E - 6\pi\eta v_r r \quad , \qquad (9)$$

where v is the particle velocity at time t. Eq. (9) describes the trajectory of particles in the vicinity of the matrix and thus provides the necessary information for the formulation of the criteria of capture[7].

Note that it is not necessary to include the effects of Brownian diffusion of small particles, since particle diffusion has no effect on the overall collection efficiency unless the dielectrophoretic forces are very weak. Other effects which may interfere, such as conduction and thermal convection, can be neglected.

In conclusion we may say that the major competing forces which determine whether or not a particle is trapped are the dielectric force, which attracts a dielectric particle to a matrix filament and holds it there, and the hydraulic force exerted by the fluid medium carrying the particle through the matrix (see Fig. 2).

Capture of particles by the matrix, particle trajectories and the zone of dielectric fraction accumulation are discussed in detail elsewhere[7].

MAIN PARAMETERS

Dielectrophoresis[5,12] is the motion of electrically neutral but polarizable particles in non-uniform electric fields. It is distinct from electrophoresis, the motion induced by the action of an electric field (uniform or non-uniform) upon a charged object. Separation of solid particles through dielectrophoresis occurs because of the tendency of matter to become polarized in a non-uniform electric field and to move into regions of highest field strength or intensity, independent of the direction of the field and the type of applied voltage, whether such voltage is in the form of alternating current, direct current or pulsating direct current. The particles having dielectric constants higher than that of the fluid medium are captured (move towards the area of greatest field intensity) while particles having dielectric constants lower than that of the fluid medium are rejected. Technically, separation may be achieved in batches or continuously.

For S-S separation, the most interesting liquids are those with high values of the dielectric constant. With a large value of

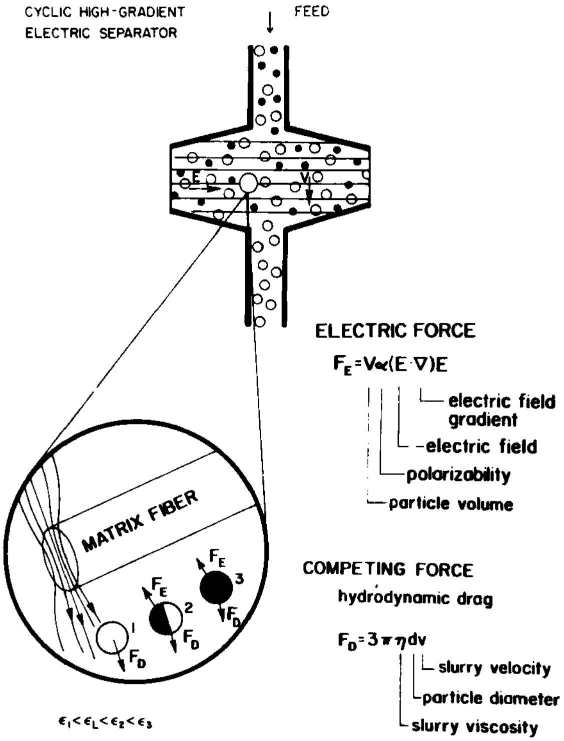

FIGURE 2

Cyclic HGES or WHIES and the principal forces acting in the system

ε_L it should be possible to use lower voltages, therefore saving energy.

For a given matrix configuration and electric field strength, the performance of an HGES device is determined by the velocity of the feed slurry through the matrix. Therefore the process is velocity-limited. The retention time of the slurry in the field is a purely dependent variable determined by the slurry velocity and the length of the matrix in the direction of flow. The length of matrix required to assure uniform flow distribution through the matrix. The total process capacity of the HGES unit is roughly proportional to the flow cross-sectional area of the matrix.

High-gradient matrix (filamentary type) structures sufficiently fine to handle colloidal particles, and sufficiently open to permit very high flow rates. The matrices are able to retain several times their own weight in collected solids and are able to release them instantly during the washing stage. By using matrices, consisting of smooth spherical ceramic perovskite compounds, glass beads or rods, etc., separation of electrically conductive materials may be very effective. This type of matrix causes these particles to be collected preferentially at the points of contact, thus preventing them from bridging across the electrodes and shorting out of the high voltage field.

A filter of this type is very effectively cleaned by first de-energizing it and then back-flushing with sufficient vigour to cause the beads, spheres, or short rods to agitate violently. This not only releases the trapped material but prevents any tendency of it to harden or to adhere to the beads etc.

The duty cycle of a static or a cyclic HGES device is that part of the total operating time during which feed material is passing through the matrix (with the electric field activated), expressed as a percentage:

$$\text{Duty cycle} = \frac{\text{Feed Time}}{\text{Feed + Rinse + Flush Time}} \times 100 \quad . \qquad (10)$$

The performances of two units of different matrix length but otherwise identical will be approximately equal if the feed, rinse and flush volumes are all scaled directly proportional to the matrix volume or, as in the present case, to the matrix length. This scaling is also necessary if the feed, rinse and flush velocities are to be kept constant.

An alternating voltage applied to the electrodes produces the same basic result as a direct voltage except that a.c. helps in avoiding bridging and trapping of particles in the matrix. By applying alternating voltage jigging and shaking are induced in the system, leading to better selectivity both in S-S and S-L separation.

Dielectric separation depends crucially on the correct optimization of such variables as matrix configuration, background field intensity, flow velocity, matrix loading, particle size and surface, chemical environment, particle colloidal stability, and others. Generally speaking, all operational variables are determined experimentally. In principle, the two types of HGES and WHIES devices, the cyclic and the continuous, are similar to their HGMS and WHIMS counterparts. In the two first-named devices, the matrix may be static in the cyclic, and moving in the continuous, variety. In a special design of a continuous unit the matrix may be static and the pair of electrodes may move continuously from the feed station. The electrified field in a cyclic device is removed during the flushing phase, whereas in a continuous device it is maintained.

Separation efficiency and the duration of the separation cycle for any given S-L or S-S system is predetermined by means of laboratory-scale tests. This ensures the faultless performance of the system and a high collection rate of particulates and it permits termination of separation before the onset of over-saturation with particulates. It also enables the optimum flow rate and operating voltage to be assessed.

When sharp separation is not attainable in a single pass through the cell, more cycles of treatment are required.

TECHNICAL REQUIREMENTS AND MAIN APPLICATIONS

It now seems appropriate to consider the features that are desirable for a dielectric separator to give a low cost per processed unit:

- high duty cycle
- high production rate
- high-quality S-S or S-L separation
- suitable matrix so as to assure easy cleaning and low loss of pressure drop
- automatic operation
- low power requirements
- low capital and running costs
- simple operation and maintenance

- separation of particles even in the submicron range, including coloured bodies, in order to achieve a brighter oil.

To date, Petroleum refineries and the vegetable oil, and metal industries, operate the only commercial applications of this technology, because in them contamination by solids is a major problem in feedstocks, distillates, hydrocarbon-based products, and other chemicals. However, because of its ability to process colloid systems more rapidly than other, more traditional separation technologies (barrier and depth filtration, centrifuging, settling/decanting, etc.), a wide range of applications in mineral processing, the petrochemical industry, waste treatment, and chemical and biochemical engineering, can be suggested and have actually been the subjects of various experimental studies at the Mineral Engineering Center, Technion.

In many applications, the use of conventional filtration has proved to be very expensive, due to the need for frequent cartridge replacement and working under high pressure and at low capacity. Dielectric filtration promises to minimize operating expenses, increase efficiency, and reduce the loss of production time required by normal bed-skimming operations.

The various ways in which HGES and WHIES can be utilized are:

1. When a difference exists between the dielectric constants of a given mineral and a liquid (in S-L separation), they can be separated to achieve clarification and liquid polishing.

2. When a difference exists between the dielectric constants of two dielectrics, the two can be differentially separated (S-S separation), even though they are of colloidal size.

3. When the particles to be collected have low dielectric constants, they can be separated by scavenging or coagulating with special seeding materials having high dielectric constant, $\varepsilon_S > \varepsilon_L$ (such as colloidal TiO_2, titanates, or other metal powders, etc.) which can then be removed with the HGES unit.

This modification may be called "piggy-back dielectric filtration".

4. Separation is also possible when an organic dissolved species can be precipitated or co-precipitated on to a dielectric "carrier".

A variety of potential applications of HGES and DF may now be suggested:

- In the metal-working industry. Removal of metallic fines from metal - working fluids, e.g. in foil rolling, where contamination of recirculated rolling oils with metal fines leads to excessive pinholing.
- In the petroleum industry. Removal of fine particulates from refinery streams.[6,13] For example:
  (a) Removing FCC catalyst fines from decanted oil (see Fig. 3) for the production of low-ash carbon-black feedstock or fuel oil. High-volume feed streams for fixed bed reactors, such as hydrodesulphurizers, hydrotreaters, hydrofinishers, etc., contain low levels of solids, but in time these accumulate and plug the catalyst bed, causing a reduction in throughput and possible reactor shut-down.
  (b) Utilizing the Gulftronic Separator (developed by Gulf Science and Technology Company, U.S.A.) for the removal of aluminium and other particles from petroleum-distillate-type rolling oils (see Fig. 4).
- In the chemical industry. For use with distillate streams, where suspended solids cause plugging in fixed-bed catalytic reactors. Particulate materials in these streams, such as coke particles, catalyst fines, and corrosion products, are easily separated. In the chemical processing, the recovery of weakly dielectric fine precipitates by deposition on highly dielectric particles may also be included under this heading.
- Treatment of minerals. Ilmenite[7,14], cassiterite, titanium dioxide, etc., are amenable to the method, which is economical provided the price of the liquid is not prohibitive. The up-

GULFTRONIC SEPARATOR SYSTEM
PERFORMANCE DATA
FCC DECANTED OIL

STREAM	TEMP °F	ASH CONTENT (WT %) BEFORE	AFTER
1	280	0.22	0.04
2	280	0.18	0.04
3	280	0.29	0.05
4	305	0.11	0.02
5	300	0.13	0.01
6	305	0.10	0.01
7	310	0.32	0.01

TYPICAL GULFTRONIC SEPERATOR INSTALLATION

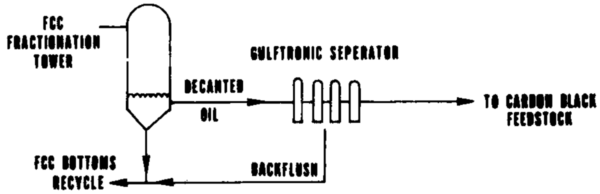

FIGURE 3

The industrial Gulftronic separation system: performance data (removing FCC catalyst fines from decanted oil).

grading of precious metal concentrates (production of material of very high value from a low volume starting material) is another example.

- Removal of ash from solvent-refined coal.
- In the waste reclamation industry:
  (a) Recovery of industrial diamonds.
  (b) Effluent and waste-liquid treatment for the recovery of dielectric materials. DF can be used to recondition petroleum products contaminated by debilitating particulates. Examples: used hydraulic fluids and used transformer oils.

FILTRATE DATA
COLD MILL ALUMINUM ROLL OIL

Sample No.	% Ash Before Filtration	% Ash After Filtration
1	0.004	0.001
2	0.019	0.001
3	0.240	0.004

PARTICULATE MATTER COUNT
SAMPLE NO. 3

Micron Range	Before	After
5-10	83,000,000	28,400
10-25	121,000,000	1,450
25-50	13,600,000	180
50-100	406,000	27
100-250	4,000	0

FIGURE 4

Removal of impurities from cold-mill aluminum rolling oil - DF filtration data.

(c) Regeneration of commercial frying oils which have picked up color and a significant solids content.

- Applications in the chemical, food and metal industries.[15]
- Applications in pharmaceutical and cosmetics processing.
- Biological applications.[16]
- In liquid treatment. Suspended or dissolved dielectric solids are amenable to treatment by DF. Separation of low-dielectric suspended particulates can be achieved by means of "dielectric seeding" or "dielectric flocculation".

- In the food industry. Examples of the processing of edible fats and oils are the dielectric filtration of nickel or copper hydrogenation catalysts or of decolorizing agents such as bleaching clays or activated carbon (see Figs. 5 and 6).
- Acceleration of sedimentation via the dielectric precipitation of dispersed particles.[17]

The three unique and advanced techniques, HGES, WHIES, and DF, may also serve as analytical or control tools for laboratory study purposes:

1. Controlling the purity of non-conducting liquids, e.g. lubricating systems.
2. Determination of wear and corrosion in liquids. Inspection and examination of the debris collected by this method can be very informative as to the condition of an engine (abrasion and wear).
3. Sensitive separation of monofractions for rapid testing and identification of minerals and other materials, e.g. for standard routines in mineralogical studies.
4. Calculation of dielectric characteristics of disperse systems.

CONCLUSIONS

Dielectric filtration and separation is a highly variegated subject, of considerable interest and value to many industries. The potentialities of this unique technology are not sufficiently widely appreciated, and they are worthy of being much more widely applied, to considerable advantage. High-gradient electric separation is a new technique which provides a practical means for separating and fractionating dielectric materials down to colloidal particle size. This method is operating on a large scale and at flow rates hundreds of times faster than the flow rates possible in ordinary mechanical filtration. The process offers singular capabilities, and a number of separations are demonstrable in the laboratory with minimal equipment.

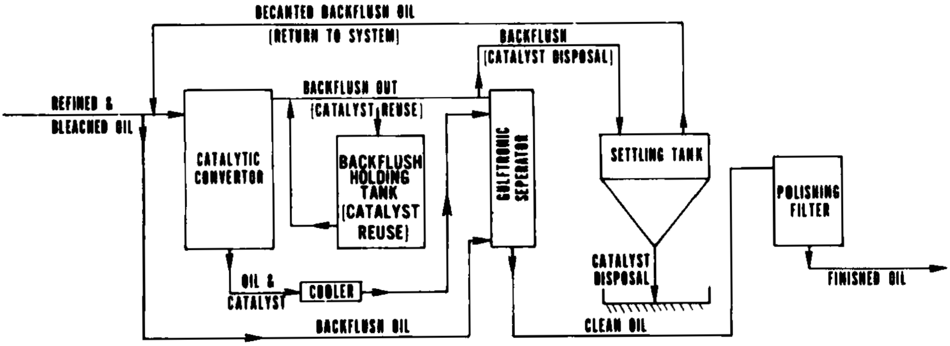

DIAGRAM OF TYPICAL APPLICATION

GULFTRONIC SEPERATOR -

VEGETABLE OIL HYDROGENATION PROCESS

FIGURE 5

Diagram of a typical application of the Gulftronic separator in a vegetable oil hydrogenation process.

The separation process, in both HGES and WHIES, can be carried out in one of two possible modes: either by direct application of electrical forces or by causing a change in the dielectric constant of the liquid medium in which the solid particles are placed. The ability of non-uniform electric fields to produce separation in suspensions of conducting and of non-conducting materials in non-polar fluid media is well established. Particle size down to the submicron range is amenable to this type of separation.

Dielectrophoresis causes motion of the particles, the direction of motion being independent of that of the field, in other words, either dc or ac voltages can be employed. The two kinds of voltages affect S-S and S-L separation efficiency to different degrees. Although the electric force varies as the square of the field strength, hence is independent of the sign of the field, and it is therefore permissible to assume that the effect of both ac and dc voltage is the same. The mechanical effects caused by the ac

FILTRATION DATA
HYDROGENATION PROCESS
SOYA BEAN OIL + NICKEL CATALYST

BEFORE FILTRATION		AFTER FILTRATION	
ASH %	NI PPM	ASH %	NI PPM
0.34	1,000	0.004	6
0.86	460	< 0.001	0.5
0.21	198	0.003	4.5
0.082	315	0.005	7.5

PARTICULATE MATTER COUNTS TWO SAMPLES				
MICRON RANGE	BEFORE	AFTER	BEFORE	AFTER
0-5	510,000	51,000	10,000,000	25,000
5-10	60,800	3,550	361,500	11,100
10-25	37,400	910	120,900	4,210
25-50	4,060	252	4,400	540
50-100	426	34	300	27
100-250	20	0	8	2

FIGURE 6

DF data for filtration in a hydrogenation process

applied voltage, however, (oscillating or pulsating current) such as jigging and shaking, lead to significant improvements in selective separation.

A greatly improved collection efficiency as compared with conventional filters may as a rule be expected from the unique performance of DF when used in S-L systems whenever solid component(s) are very finely divided and are in relatively low concentrations. Dielectrophoretic forces can be considerably larger than the viscous, inertial, or diffusion, forces normally associated with the filtration process. The matrix structure is more permeable and hence allows higher filtration rates. These trends indicate that DF is bound to become an important facet of future filtration processes.

Some other features are: DF is non-plugging and exhibits a low pressure drop during separation; the system can be constructed in modular form, and it operates continuously and automatically.

In general it can safely be stated that DF is an attractive alternative to conventional filtration/separation processes, such as cartridge filters, hydrocyclones, and sedimentation tanks, and it has, in fact, already been applied industrially.

DF, WHIES, and HGES are all well adapted to analytical work in our laboratory for mineralogical studies and ore dressing tests.[18] They serve in a variety of applications, such as dielectric material fractionation, dielectric filtration, static levitation, and dielectric constant measurement, and as a method of determining the electrical characteristics of particulates.

Summing up, it appears that HGES, WHIES and DF will almost certainly become an important technology in the next decade, penetrating into mineral, chemical, organic, biochemical, pharmaceutical, ink processing, being applicable to S-S, S-L or S-G separations and purification of particulate systems.

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