Fine Particle Separations from Nonaqueous Liquids

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Abstract

Many industrially important processes utilize or generate fine particles. These particles, which range from submicron to 100 μm in size, can have substantial impact on operations even at low concentrations. They contribute to fouling, coking, erosion, foaming, emulsion, and entrainment problems, and can cause potential environmental problems when released in the atmosphere. Furthermore, their existence presents a major barrier to the successful development of new, synthetic fuels processes. Hence, technology is needed to provide efficient separations methods. This paper briefly reviews currently available technology for fine particle separations from liquids and introduces some future directions for this technology. The focus of the paper is on clarification of nonaqueous liquid systems with emphasis on particles smaller than 25 μm. Five promising approaches are discussed: evaporative concentration, size augmentation, viscosity reduction, interphase transfer, and field- or mechanically aided separations.

INTRODUCTION

Many industrial processes utilize or generate fine particles, and subsequently require their removal from liquid streams. These particles may range from over 100 μm to submicron in size. Effective separations technology is essential because of their impact on downstream operations and product quality. Fine particles contribute to fouling, coking, erosion, foaming, and entrainment problems, stabilize emulsions, and cause potential environmental problems when released into the atmosphere. Their existence has presented a major challenge in the development of new synthetic fuels processes.

The objectives of this paper are to review briefly currently available technology for fine particle separations from liquid streams and to speculate on some future directions of this technology. The focus of this paper is on new approaches to clarification of nonaqueous liquid systems. These systems are not well covered in the literature and represent more severe operating conditions such as high temperature and pressure, large flow rates, and varying concentrations of solids. There is also a greater emphasis on particles smaller than 25 μm since this is an area where technology advances are needed.

BACKGROUND

In the petroleum refining and petrochemical industries, fine particles are usually extraneous impurities or attrited catalyst that contaminate process and product streams. The impurities come from many sources. Various salts may be introduced into crude oil in production and transportation. Although these salts are usually dissolved in water, processing of the oil causes the water to dissolve, leaving behind fine crystals. Corrosion products and attrited and entrained catalyst are also common sources of particulates. Coke particles from furnaces and thermal pyrolysis/cracking processes, such as fluid coking, contribute to the problem.

The greatest concentrations of fine particles are usually found in the heaviest, highest boiling fractions. For example, streams such as residuum and bottoms from catalytically and steam cracked feedstocks may have as much as 5000 ppm of solids. Removal of these solids is made more difficult by the high viscosity of the liquids and often requires processing at elevated temperatures.

The required degree of particulate removal is set either by a product specification or an operational problem. Maximum particulate levels in fuels are usually set by emissions limits or furnace fouling/slagging concerns. Specifications may also be based on the maximum levels of a particular impurity. In these cases the particulates need to be removed because of their chemical composition. For example, a marine bunker fuel may have a 30-ppm maximum aluminum specification. The aluminum is due primarily to attrited catalyst that had an alumina base.

Fine particles are particularly troublesome in processing because of the operational problems they cause. Fine particles cause fouling of heat exchangers, towers, and fixed-bed reactors. Even though the particles are very small, numerous instances of excessive pressure drop and catalyst deactivation have been traced to the deposition of these fines. Heat

exchanger fouling by fine particles has also been reported (*1*). In both cases, particle adhesiveness is believed to be a contributing property.

Bikerman (*2*) has indicated that noncoloidal particles smaller than 50 μm can and do stabilize foam. Foaming in process equipment results in liquid entrainment, cavitation of downstream pumps, and ineffective contacting in distillation. Similarly, fine particles tend to stabilize emulsions, resulting in ineffective separator drum operation and entrainment from extraction towers, with consequent product losses, energy debits, and corrosion.

Fine particle separations are a major issue in the development of synthetic fuel processes that produce liquid hydrocarbons from nonconventional sources such as coal and shale. Adequate handling and removal has a significant influence on process economics and viability. For example, in tar sands processing, large volumes of fine solids must be separated from bitumen containing 9 to 12 wt% solids (*3, 4*).

During the 1970s, several coal liquefaction processes were being developed and a central issue was removing the ash and unconverted carbon from the reactor effluent or distillation tower bottoms. Solids concentrations of 40 wt% and 1 to 5 μm mean particle sizes were typical. Target levels for use as a "new source" fuel were 1500 ppm ash. Consequently, several studies were done to establish the most appropriate technology. These are summarized in a review paper by Briggs et al. (*5*).

Shale is the synthetic fuel of most current interest. The usual approach in shale processing is to crush and then retort the ore, freeing the kerogen. The recovered oil is then upgraded. The amount and size of the fines produced depends on the shale mineralogy as well as the retort type, design, and operation. Solids loadings in the whole raw shale oil of 6 wt% with mean particle sizes of under 10 μm have been reported (*6, 7*). The level of departiculation required for these plants will depend on the upgrading scheme.

SUMMARY OF CONVENTIONAL TECHNOLOGY

Several techniques are available for removing fine particulates, and various selection schemes have been proposed. Selection of the most appropriate device depends primarily on particle size distribution, concentration, liquid viscosity (or temperature), liquid loss, and cost. The area where technology is most deficient is removal of moderate to high concentrations (0.1 wt% and up) of very fine particles (under 25 μm) from liquids with viscosities greater than 10 cP (or at temperatures above 175°C).

Presented below is a brief summary of capabilities, advantages, and limitations of conventional solid–liquid technologies as applied to fine particle separations.

Precoat Filtration

Precoat (diatomaceous earth) filters, such as rotary drum or vertical leaf filters, can effectively remove particles as small as 1 μm from liquids at temperatures up to about 250°C. They are often utilized for clarifying chemical products and for removing low concentrations of scale, rust, and coke or catalyst fines from process streams such as monoethanol amine (MEA) gas-treating solutions. These types of filters have been automated to a great extent. A considerable amount of research was done on precoat filters for removing fines from coal liquids (8). In these studies, typical solids concentrations were about 5 wt% and particle sizes ranged to below 10 μm.

There are several drawbacks to using precoat filters. Precoat feeding, storage, and disposal facilities for the solids and precoat are needed. Liquid losses can also be high. In addition, for liquids with high solids concentrations, filtration rates are low, usually below 0.4 $m^3/h \cdot m^2$ (10 gph/ft^2.) This translates to high capital costs for the necessary surface area. In coal research work, many mechanical problems were also noted. Operating costs are high because of the precoat and body feed requirements and required labor. In addition, the large-scale projected usage of diatomaceous earth could not have been easily supplied.

Media (Nonprecoat) Filtration

To avoid the precoat disposal problems and simplify the operation, nonprecoated filtration using fine screens, fibrous mats, and other porous media has been applied in various services. However, applications to fines removal from hydrocarbon streams has been limited because of high pressure drops, low solids holding capacities, and the cost of suitable filter media. Recent advances in filter technology have included systems which are self-cleaning or have automatic backwashing capabilities, and the development of improved media.

Filtering of particles finer than 25 μm is limited by blinding of the filter media and the highly impervious cakes that form. Cake resistances greater than 10^{12} kg/m are not uncommon, and filtration rates drop off very rapidly. For example, Table 1 shows initial filtration rates and rates after 15 min on various media for a carbon black oil containing 3000 ppm of 15 μm particles. Furthermore, media blinding by particles or tarry, asphaltenic material can

TABLE 1
Filtration Rates for Carbon Black Oil[a]

	Filtration rate		
Media	Initial ($cm^3/min/cm^2$)	15 min ($cm^3/min/cm^2$)	Average retention (%)
Dutch Twill-80 × 700 mesh	6.00	0.93	75
Porous Sintered Metal SS 304	2.31	0.48	94
Dutch Twill-165 × 1400 mesh	2.00	0.40	94
Porous Sintered Ni-4 μm	1.32	0.36	95
Dutch Twill-200 × 1400 mesh	1.22	0.41	88
Dutch Twill-325 × 2300 mesh	1.16	0.30	89
Bonded metal fiber	1.14	0.29	94
Electroplated wire mesh: 10 μm	1.07	0.35	88
5 μm	0.46	0.31	97
3 μm	0.46	0.10	95

[a] Feed: Carbon black oil with 3000 ppm solids, mean particle size of 15 μm.

reduce filtration rates. Filtration is therefore usually not used unless particle concentrations are low.

Automatic self-cleaning filters are sometimes attractive when high resistance cakes are formed. These devices use a backflush, shock vibration, or a high-speed rotation to remove particles when the pressure drop reaches a preselected level. Backwashing filters, shown schematically in Fig. 1, with 25 μm nominal slot size have found use in protecting fixed-bed reactors in heavy oil hydrodesulfurization service (9). For finer particle filtration, short cycles, low loadings, and mechanical problems have limited application of these devices.
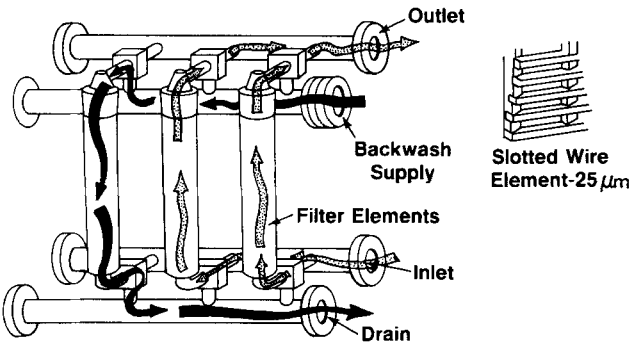

FIG. 1. Automatic backwashing filter.

Granular bed filters are sometimes used for protecting process equipment from scale or coke. The filtration media can be sand or spent catalyst. These filters are usually limited to concentrations below 100 ppm because of their low capacity and to process streams with particles greater than 25 μm in size. Smaller particles can sometimes be captured on sand as coarse as 50 mesh (300 μm). However, the efficiency of capture is low.

Centrifugation

Two principle types of centrifuges are used for removal of fine solids: solid bowl-scroll discharge and disk machines. Solid bowl machines are generally used to remove particles that range in size from 50 to several hundred microns. Disk machines usually produce a lower solids content liquid product and are useful for removing particles down to about 5 to 10 μm.

In general, for high capacity applications, the solid-bowl machines do not have the clarification capabilities that are built into the disk machines. Frequently, when the solids concentration is high, the two machines are used in series—the solid-bowl for bulk removal and the nozzle-disk machine for clarification with the nozzle effluent recycled to the solid-bowl feed. Such a configuration has been reported for departiculating tar sands bitumens at the Syncrude plant in Alberta (4). A bitumen containing 9 wt% solids of about 40 μm mean size is diluted with naphtha. The first stage uses solid bowl centrifuges to remove 50% of the solids as a cake (~45 wt% solids content). The second stage uses nozzle-disk machines and produces the feed to the cokers containing less than 1.5 wt% solids.

While centrifuges can be used for fine particle separations, there are some drawbacks. As particle size decreases or viscosity increases, the residence time must be increased to get good performance. This means the capacities are low for equipment processing streams with very fine particles or viscous liquids. Mechanical problems such as erosion and sealing problems have been reported in various coal liquefaction studies (10).

Hydroclones

Hydroclones (liquid cyclones) are attractive alternates for separating fines from liquids because they have no moving parts, can operate at high temperatures, and can achieve a higher concentration of solids than nozzle-disk centrifuges. However, they are sensitive to flow conditions and subject to abrasion and/or plugging problems. Clarification capability is normally not as good as that of a disk centrifuge.

The capability of a hydroclone to remove fine particles is a function of the hydroclone diameter. For particles under 50 μm, only hydroclones with diameters less than 25 mm are suitable. The smallest available size, 10 mm in diameter, is effective at removing particles down to about 10 μm. Therefore, many small diameter hydroclones must be used in parallel, and high pressure drops may be required. Loss of liquid in the slurry underflow can also be a serious debit.

Sedimentation

Gravity settlers can be an inexpensive and simple method for handling rapid settling particles in low viscosity liquids such as aqueous systems. Separation can sometimes be enhanced by the addition of several close-spaced, sloped settling baffles. However, settlers are not generally useful for hydrocarbon systems with particles smaller than about 50 μm, because the low settling velocities result in unacceptably large tanks. With flocculants to promote agglomeration, much finer particles can be effectively removed; however, flocculant selection is very empirical. Temperature limitations and oil loss in the underflow or sludge are also limitations.

EMERGING TECHNOLOGY

There are a number of relatively new concepts being developed for separating fine particles. Some of these have already been commercialized although they haven't had widespread application. These techniques can be grouped into five broad methods: evaporative concentration, size augmentation, viscosity reduction, interphase transfer, and field- or mechanically aided separations.

Evaporative Concentration

Vacuum distillation can be an effective evaporative technique for producing clarified product and concentrating the solids in a hydrocarbon bottoms product. This method was used in the EDS Coal Liquefaction process for recovering liquid products and producing a bottoms feed for fluid coking or partial oxidation (11). Other coal liquefaction processes such as H-Coal achieved bottoms products containing 40 wt% solids with less than 0.1 wt% in the distillate (12). The disadvantages of this approach include
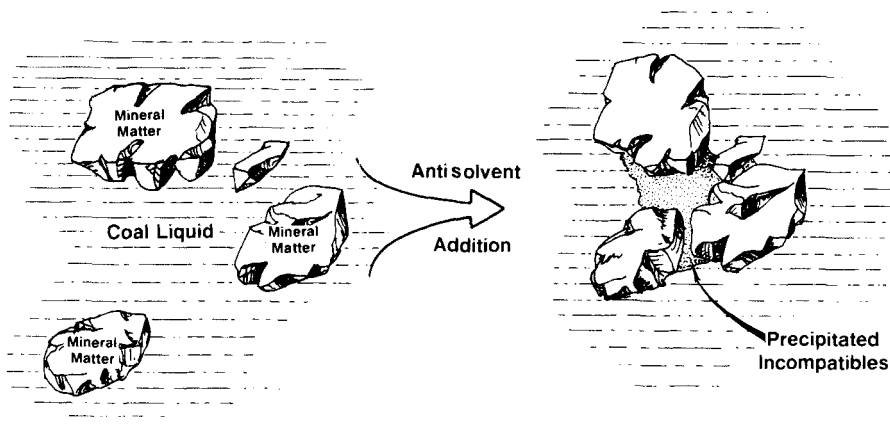
FIG. 2. Antisolvent addition causes agglomeration.

potential fouling or coking problems in exchangers, furnaces, trays in the tower, and higher energy usage. The particle size distribution is critical in determining the amount of entrainment of solids into the flashed liquid.

Size Augmentation

Increasing the effective particle size is a general approach to improving separations of very fine particles. In water treatment, flocculants are used to increase particle size. Little has been done with hydrocarbon liquids. Additives can be used as flocculating agents in organic liquids (13). Presumably the additives adsorb and change the wetting or adhesive characteristics of the surface. Table 2 compares the effectiveness of various chemicals for settling fines in carbon black oil. The fines have a mean size of 15 μm. As evident from Table 2, settling and, presumably, agglomeration are enhanced by these chemicals.

Another size augmentation technique for hydrocarbon liquids involves the addition of an antisolvent to the slurry. The solvent modifier produces a liquidlike precipitate which agglomerates the fines which can then be removed by conventional techniques like settling or centrifugation. This is shown schematically in Fig. 2.

One application of this method was in work with coal liquids during the EDS process development. The addition of a low boiling, low aromaticity hydrocarbon fraction, e.g., 10 to 20% of a fractionator overhead stream, markedly improved centrifuge performance (11). The clarity of the centrate

significantly increased at approximately the same rates and temperature, e.g., percent ash in centrate was reduced from 0.4 to 0.1%. At the same clarification level, feed to the centrifuge could have been increased by about 25% over typical rates. Changes in viscosity or density alone would not have accounted for this improvement. The precipitated phase represents a very small loss of product since it consists of marginal quality components.

Antisolvents were also found effective with liquefied coal slurries from the COED and SRC processes (14). The addition of 20% toluene to unfiltered SRC oil greatly increased settling rates. Based on settling data, the smallest agglomerate was estimated to be 53 μm whereas the fine particles were about 1 μm. Optical microscopy showed the agglomerate to contain 100 particles or more. Once agglomerated, the particles could easily be removed by settling or filtration. Filtration rates of the SRC agglomerated coal were two to four times as large as with the unagglomerated fines.

The Lummus antisolvent process was tested in an SRC pilot program in Ft. Lewis, Washington. In this process the liquefied coal slurry is first fractionated to remove light ends. The slurry is then mixed in a 2-to-1 ratio with SRC antisolvent. The mixture is then settled. The overflow is sent to fractionation to recover the antisolvent, and the underflow is sent to a stripper and vacuum unit to recover the antisolvent and liquid product. The vacuum bottoms, containing 40 wt% solids, is sent to a gasifier. In the Ft. Lewis test, overflow clarity of 0.2 wt% or 98% departiculation was achieved. However, recovery of the SRC liquid was only about 70%. Attempts to increase the overflow-to-underflow ratio resulted in decreased product quality (8).

Antisolvent techniques are not limited to coal liquids. For example, antisolvents were found to be beneficial in removing solids from a crude oil tank sludge that contained 10% fine solids and 25% water. As shown in

TABLE 2
Additive Enhanced Gravity Settling of Fines in Carbon Black Oil[a]

Additive	Dosage (ppm)	Ash level in CBO after 5 h (% reduction)	Ash level in CBO after 18 h (% reduction)
Blank	0	27	56
Aqueous polyamine	150	67	91
Aqueous cationic polyelectrolyte	20	93	Not measured
Ethoxylated phenol formaldehyde resin	500	64	71

[a] Feed: 2000–3000 ppm fines.

TABLE 3
Antisolvent Sedimentation of Tank Sludge[a]

Antisolvent (cm/h)	C/H ratio	Initial rate
None	—	1
Hexane	0.429	12
Pentadiene	0.625	30
Toluene	0.875	56
Benzene	1.000	65

[a]Sludge: solids 10.6 wt%; water 14.7%; 74.7% oil.
Temperature: 120°C.
Solvent/oil ratio: 0.5 (by weight).

Table 3, the addition of solvents with a high carbon-to-hydrogen ratio increased the initial settling rate. With highly aromatic coal liquids, low C/H ratio solvents (15) are effective, while with paraffinic sludges, high C/H ratio solvents are better.

Farnard et al. (16) have described the process of spherical agglomeration of fine particles in hydrocarbon liquids. In contrast to the antisolvent technique which forms a liquidlike precipitate, the key to this technique is to add a second liquid that preferentially wets or absorbs on the solid surface and acts as a bridging agent between particles. For example, a 10 wt% fine graphite suspended in Varsol was flocculated with the addition of 5% aqueous tannic acid solution.

Finally, ultrasonics may be an interesting technique for agglomerating fines. The literature is very limited on this subject. However, the Russians report success in agglomerating 20 μm iron oxide particles and water droplets suspended in oil (17). By exposure to low frequency ultrasonic energy, the particles grew to 90 μm in size. The use of additives together with ultrasonics would appear to be an interesting area for future research.

Viscosity Reduction

Another approach to improving fine particle separations is to reduce liquid viscosity. Supercritical solvent deashing is a technique that falls in this category.

In deashing, the solids-containing liquid is mixed with a solvent that is near or above its critical point. The process is shown schematically in Fig. 3. The solvent lowers the viscosity and allows rapid settling of the solids in the first stage settler. The solids are removed as a concentrated underflow. Solvent recovery from the underflow can be accomplished by depressurization and

stripping. Finally, the solids are discharged as a "dry" powder. In some cases the solvent can extract oil which may be in the pores of the particles. The solvent may also precipitate oil constituents which promote agglomeration, similar to the antisolvent technique. The light phase from the settler is heated slightly to decrease the solvent density and, hence, the solubility of the oil. Two phases form and are then separated—the solids-free oil product from the bottom of the solvent separator and the recovered solvent from the top.

Supercritical solvent deashing has been tested for removing ash from liquefied coal (*18*). In these tests the vacuum feed slurry containing 14 wt% ash was mixed with 3 to 10% process solvent. The overflow liquid had an ash content of less than 0.1%. The product yield of soluble coal was 80% and was related to process conditions in the liquefaction reactors (dissolvers).

Supercritical deashing represents a promising approach for solids removal. It appears particularly useful if the feed is already available at high pressure as is the case in coal liquefaction or hydroconversion reactors. Furthermore, deashing must be closely tied in with the overall process scheme since solvent selection (hopefully process derived) and ash disposal will have significant impact on the overall economics.
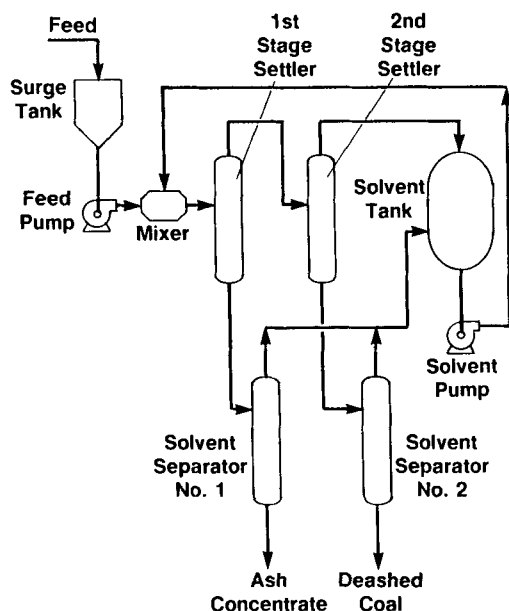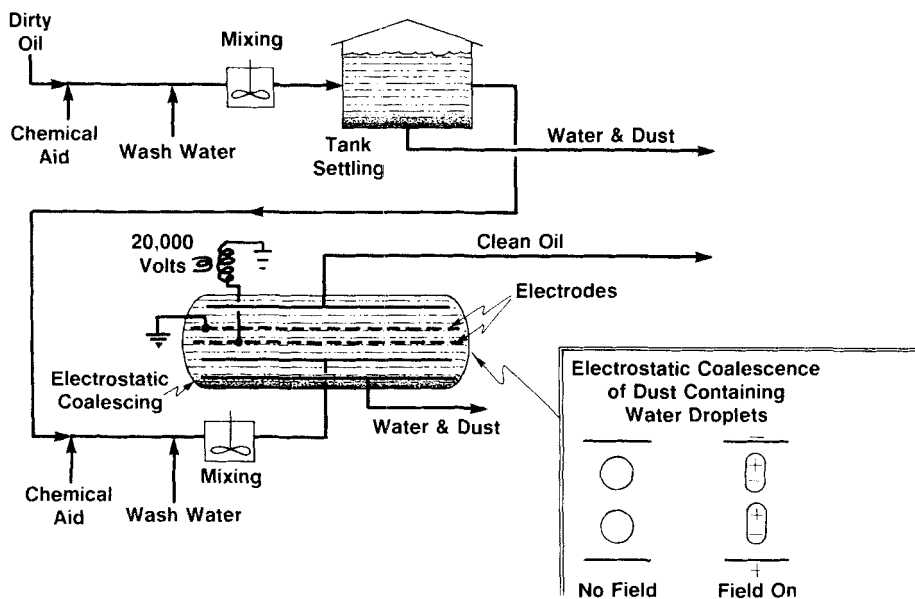

FIG. 3. Critical solvent deashing (*18*).

FIG. 4. Shale oil dedusting by water washing.

Interphase Transfer

If appreciable concentrations of solids are to be removed, it may be desirable to make the separation by transferring the solids into an aqueous phase. In this approach the oil slurry, containing as much as 15 wt% solids, is intimately contacted with water. A transfer agent either introduced in the water or oil is used to move the solids into the water phase. Suitable demulsifiers and/or mechanical means are then used to coalesce the water-in-oil emulsion and separate the water phase.

Two different approaches have been described in the literature. In work with tar sands, a froth containing about 10 wt% solids, bitumen, and water is treated with a 1% solution of tetrasodium pyrophosphate, which acts as a transfer agent and a demulsifier (19). The transfer agent promotes wetting of the solids which results in the fines removal from the oil/water interface into the aqueous phase. The water droplets coalesce and are removed, producing a clean oil.

The second example involves the departiculation of shale oil (7). Shale oil from retorting may have appreciable quantities of fines of 1 to 5 μm in size. In dedusting, the oil is mixed with an oil-soluble surfactant demulsifier and up to 10 vol% water. A simplified flow scheme is shown in Fig. 4. The

surfactant is an aryl sulfonic acid and the demulsifier is a blend of an ethoxylated phenol formaldehyde resin and fatty acid ester. The chemicals are intimately mixed with the oil and water, forming an emulsion. The chemicals cause water to wet the dust preferentially, transferring the solids to the aqueous phase. Electrostatic coalescers are used to coalesce the water droplets. Solids removal efficiencies as high as 99% are obtainable in a single-stage coalescer.

Field- or Mechanically Aided Separations

Over the past few years there has been an increasing interest in improving separations by using external fields. Most of the research and development has been directed at the use of electric and magnetic fields. There is also some indication that ultrasonic or vibrational energy may be useful.

Electric field-aided separations for fines removal from hydrocarbon liquids are based on electrophoresis or dielectrophoresis (20). Electrophoresis is defined as the transport of electrically charged particles in a uniform dc field. Suspended coal and fine particles such as ash and minerals particles in hydrocarbon liquids have been shown to carry a charge (21, 22). Hence, studies have been done to evaluate field-enhanced sedimentation rates, deep bed filtration efficiencies, and cross-flow electrofiltration.

In cross-flow electrofiltration, particle accumulation on the filter medium is minimized, thus allowing withdrawal of a clear filtrate. Particle migration away from the filter medium is due to fluid shear and electrophoretic migration. A schematic of the mass flow electrofilter by Lee et al. (23) is shown in Fig. 5. It consists of a feed pump, a dc power supply, and a tubular filter unit of porous stainless steel with a pore diameter of 5 μm. A platinum wire down the center of the tube serves as the other electrode. The metal tube serves as a ground and the polarity of the center electrode is opposite from the charge on the particles. Experiments were carried out with 1.0 wt%, 0.3 to 2 μm Al_2O_3 particles in tetralin, and H-coal liquids diluted with xylene containing 1.25 wt% solids. Fields of 1 to 10 kV/cm were used and the current was about 4 mA. Filtration rates of approximately 0.2 m^3/h $\cdot$ m^2 were achieved. These rates are comparable to those achieved with rotary precoat filters.

As previously mentioned, granular bed filtration is a widely used process for removal of scale, coke, etc. With fine particles, however, the capture efficiency is low. Chowdiah et al. (24) investigated the concept of charge neutralization in granular filtration of 0.3 μm carbon black particles
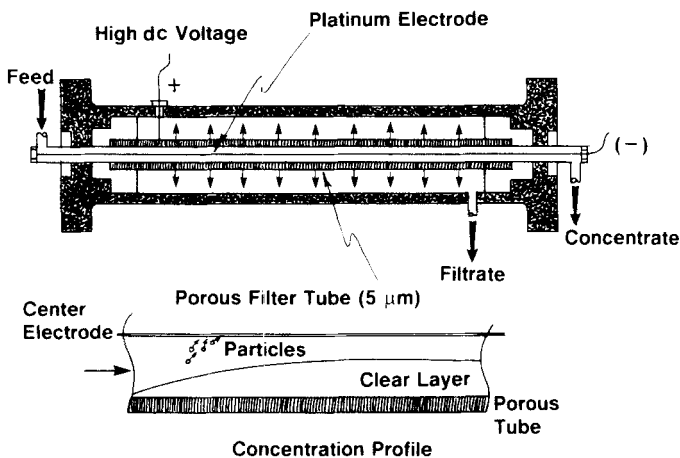
FIG. 5. Cross-flow electrofilter (*23*).

suspended in tetralin using 81 μm silica sand. The charge on the filter media and its neutralization by depositing particles was directly related to the filter efficiency.

In dielectrophoretic filtration, the application of a nonuniform electric field causes the particles to be polarized and move in the direction of the increasing field (*25*). In practice, the particles migrate and collect on the surface of a nonconducting solid (the filter media). The major problem had been the lack of a regenerable filter media. However, Gulf Research (*26*) and Petrolite Corp. (*27*) have overcome this problem by using hard, smooth, spherical glass beads about 0.6 cm in diameter.

These types of electrofilters are commercially available, and there have been several installations involving departiculation of catalyst fines from carbon black oil (*28, 29*). In operation (see Fig. 6), the fines collect on the filter media until a preset pressure drop is reached. The field is then shut off and the medium backwashed, producing a concentrated slurry for disposal or recycle. Product solids levels of less than 100 ppm have been achieved with a single stage of electrofilters processing a feed containing more than 3000 ppm of fines.

Electrically enhanced filtration devices have several potential advantages over more conventional equipment. Unlike centrifuges or hydroclones, their performance is less sensitive to particle size. A cross-flow electro-filter can handle submicron particles; dielectrophoretic filters can remove particles under 5 μm. Pressure drops are also much lower than with

comparable mechanical filters. For example, the pressure drop across a 2-m high electrofilter bed loaded with catalyst fines is about 140 kPa. The pressure drop across a 5-μm element from a backwashing filter comparably loaded can be as high as 750 kPa.

There are some drawbacks which have limited commercial applications. First, these devices are usually limited to low conductivity fluids, typically below 10^{-9} mho/m. With carbon black oil, energy consumption was about 1 J/cm^3 of fluid at temperatures up to 80°C. However, at higher temperatures, the conductivity and power consumption increased significantly. For this reason, the concentration of any free water must also be kept low. The feed solids concentration is limited to about 1 wt%. There has been very little work done on the scale-up of cross-flow electrofilters.

Weakly magnetic fine particles can be removed by using a high gradient magnetic separator (HGMS). The magnetic force on a particle depends on
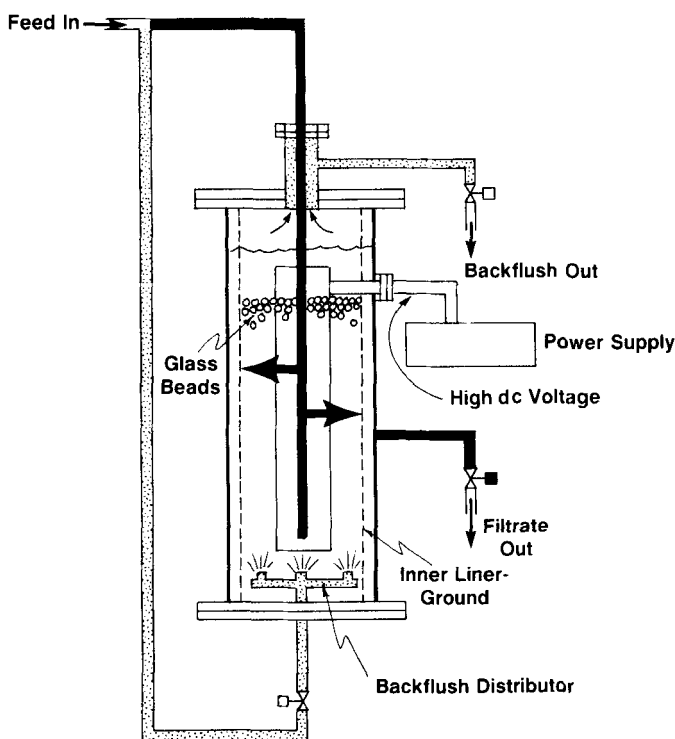

FIG. 6. Radial flow electrofilter.

the field gradient, particle volume, and particle magnetization (a function of the inherent magnetic properties of both the particle and field). To remove very fine particles requires a very strong field gradient. To achieve a high gradient in a commercial device, a steel wool matrix is used as the capturing medium. The matrix is surrounded by an electromagnetic coil capable of producing fields of 20 kG. When the field is activated, ferro- and paramagnetic particles are trapped while nonmagnetic material and fluid pass through. In cyclic units the matrix is loaded until a preset pressure drop is reached. The field is then shut off and the matrix backwashed. For high solids loadings, continuous feed units are used which have the matrix mounted in a rotating ring (*30*).

HGMS have been used in minerals processing applications including kaolin clay purification and benefication of iron ores. In water treating they have been used for impurity removal. When the particles are nonmagnetic, flocculants and magnetite seed particles are added. In petroleum refining, HGMS may be used for removal of contaminants such as iron sulfides from product streams. Research has also been done on this technique for removal of pyritic sulfur compounds in SRC liquids. Removal of paramagnetic shale dust from shale oils has also been reported (*31*).

HGMS can be very effective, especially as a polishing device when the particles are magnetically susceptible. If the solids concentration is high, the backflush effectiveness, disposal of the concentrated slurry, and loss of oil must be considered. The use of magnetic seeding combined with additives could be an interesting way of handling nonmagnetic material.

Ultrasonics were previously mentioned as a way of agglomerating fines. Ultrasonic or pneumatic vibration of the filter element may also be used to improve filter performance (*17*). The principle is that the suspended particles are repelled from the vibrating surface of the filter element, preventing media blinding or cake formation. The concentration of the particles increases away from the surface, and eventually they coagulate and settle. There is little published information on this technique.

CONCLUSIONS

Fine particles in the refining and chemical industries are receiving increased attention because of their adverse impact on operations. As feedstocks get heavier, the need for separations technology will also increase. The eventual development of a synthetic fuels industry will change the role fine particle separations currently fulfill. These techniques will be key steps in

new processes. A considerable amount of technology is already available. However, there is a need for improved techniques to handle high concentrations of particles under 25 μm in viscous liquids.

Several recent developments to enhance fine particle separation appear attractive. These methods are based on physical, chemical, and surface interactions between particles and the liquid phase or phases, and between particles and various fields. The combination of these methods with each other or with conventional techniques might result in synergistic effects. For example, the use of chemical additives such as surfactants or antisolvents with fields or filter media may be a fruitful area for engineering research. Fundamental studies on particle–liquid interfacial behavior would also contribute to the development of improved technology.

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