Fabric filtration is the surest means of removing fine particles. EPRI has devised the 'Compact Hybrid Particulate Collector' (COHPAC). This design simply places a baghouse after an ESP. The ESP removes much of the particulates, easing the load on the baghouse, hence reducing maintenance. The baghouse reduces pollution due to rapping loss, and is insensitive to changes in fuel.

EPRI has also developed an 'EPRICON' process which can replace conventional chemical conditioning of fly ash from low sulfur coals. In this process, a portion of the gas stream is diverted to a vanadium oxide-based catalytic unit, which efficiently converts SO_2 to SO_3. Recombination of the treated stream with the bulk results in the necessary conditioning of the fly ash.

See also: **Particle Size Separation:** Hydrocyclones for Particle Size Separation; Sieving/Screening.

Further Reading

Busby HGT and Darby K (1963) Efficiency of electrostatic precipitators as affected by the properties and combustion of coal. *Journal of the Institute of Fuel* 36(268): 184.

Dubard JL and Nichols GB (1990) Diagnosis of electrical operation of electrostatic precipitators. *Journal of Electrostatics* 25: 75.

Hart BR, Powell MA, Fyfe WS and Ratanasthien B (1995) Geochemistry and mineralogy of fly-ash from the Mae Moh lignite deposit, Thailand. *Energy Sources* 17: 23.

Kanazawa S, Ohkubo T, Nomoto Y and Adachi T (1993) Submicron particle agglomeration and precipitation by using a bipolar charging method. *Journal of Electrostatics* 29: 193.

Landham EC Jr., Dubard JL and Piulle W (1990) The effect of high-voltage waveforms on ESP current density distributions. *IEEE Transactions on Industry Applications* 26(3): 515.

McKinney PJ, Davidson JH and Leone DM (1992) Current distributions for barbed plate-to-plane coronas. *IEEE Transactions on Industry Applications* 28(6): 1424.

McKean KJ (1988) Electrostatic precipitators. *IEE Proceedings Pt. A.* 135(6): 347.

Oglesby S Jr. and Nichols GB (1978) *Electrostatic Precipitation*. New York: Marcel Dekker Inc.

Tachibana N (1989) Back discharge and intermittent energization in electrostatic precipitation of fly ash. *Journal of Electrostatics* 22: 257.

Watanabe T, Tochikubo F and Koizumi Y *et al.* (1995) Submicron particle agglomeration by an electrostatic agglomerator. *Journal of Electrostatics* 34: 367.

Zhibin Z and Guoquan Z (1994) Investigations of the collection efficiency of an electrostatic precipitator with turbulent effects. *Aerosol Science and Technology* 20: 169.

Field Flow Fractionation: Electric Fields

S. N. Semenov, Institute of Biochemical Physics, Russian Academy of Science, Moscow, Russia

Introduction

Field flow fractionation (FFF) represents a class of separation techniques, which use a force field perpendicular to the direction of separation to control the longitudinal velocity of particles injected into the system. It is achieved by particle redistribution in the flow with a parabolic velocity profile due to the action of a transverse force. This transverse force may be due to an electric field, a centrifugal or gravity field, etc. In electric FFF (ElFFF), the transverse movement of the particles is caused by an electric field. The transverse particle velocity, U, is defined by the expression:

$$U = b \cdot E \qquad [1]$$

where b is the particle electrophoretic velocity, and E is the electric field strength in the channel interior, which is available both for the particles and the flow of the carrier liquid. The particle electrophoretic mobility is related to the particle electrokinetic potential (zeta-potential):

$$b = \frac{\varepsilon\zeta}{4\pi\eta} f\left(\frac{R}{\delta}\right) \qquad [2]$$

where ε is the dielectric constant of the carrier liquid, η is the carrier liquid viscosity, ζ is the particle electrokinetic potential, R is the particle diameter, and δ is the Debye length characterizing the screening of the electrostatic interaction in an electrolyte. $f(R/\delta)$ is a function changing monotonously from 1 for particles of $R \gg \delta$ to 1.5 for small particles, when the zeta-potentials are small. For higher zeta-potentials, this function approaches a minimum of less than one. Thus, the particle electrokinetic potential and electrophoretic mobility represent the parameters slowly changing with the particle size and depending mainly on the surface properties of the particle. For small objects like macromolecules and low-molecular-weight ions, the theory of the electrophoretic mobility is absent.

For the characteristic relaxation time, the Boltzmann transverse particle distribution is established in the system by forcing injected particles toward the wall of the channel and their thermal (diffusion) motion. In ElFFF (reported as the method for protein separation), particles of the same size with higher electrophoretic mobility or zeta-potential will accumulate more closely to the wall, while particles of lower zeta-potential will form a more diffuse layer that extends further into the flow of the carrier liquid. Proteins still represent most of the ElFFF sample materials. For particles with about the same zeta-potential, the thickness of this layer may also be different, if the particles have different diffusion coefficients, D. Particles with higher diffusion coefficient (i.e., with smaller size) will accumulate in a more extensive layer due to more intensive thermal movement. Zeta-potential is an important parameter interrelated to the particle surface charge density, and characterizing the particle surface properties and the possible exchange of substances between the particle and the surrounding liquid, e.g. in cellular processes, including transport through cell membranes, antigen–antibody interactions, and hormonal control.

ElFFF is carried out in a thin channel of rectangular cross-section with the width to thickness ratio (aspect ratio) about 100 (thickness about 10–100 microns). It allows the separation to approximate to a laminar liquid flow between infinite parallel plates, which is characterized by a parabolic velocity profile, where the fluid velocity at the channel walls is zero and reaches a maximum in the centre of the channel. Thus, if a group of particles maintain an average distance from the wall different from another group of particles, their velocities along the channel will be different and they will leave the channel at different times, related to the particle zeta-potential and size, which defines the particle diffusion coefficient. In FFF systems, the same types of fields are used as in the so-called 'direct field methods' (centrifugation, electrophoresis, etc.), but there is no requirement of complete fraction resolution in the field direction, and field strengths may be lower. In principle, all mixtures separated by direct electrophoresis may be effectively analysed by ElFFF, if they have a size large enough to form a layer of thickness smaller than the channel thickness, even when its electrophoretic mobility is too small for electrophoretic analysis. FFF systems are elution methods and allow the collection of fractions during a separation. Since the theory of FFF dynamics is well developed, the separation times for a given sample can be directly related to the physical parameter of the particles. This parameter represents the effective particle charge q^*, which defines the thickness of the Boltzmann particle distribution $\approx \exp(q^* E \cdot x / kT)$ (x is the transverse coordinate in the channel) in the transverse electric field applied to the ElFFF channel. Using the known Einstein relationship, this effective particle charge may be defined as the ratio of the particle electrophoretic mobility multiplied by the thermal energy kT, to its diffusion coefficient:

$$q^* = kT\frac{b}{D} \qquad [3]$$

In principle, this effective charge itself represents a new separation parameter, which may be used for particle and macromolecule characterization, if the theory is developed. This theory should relate the effective charge and the particle and macromolecule physicochemical parameter important in specific applications, for example, the surface density of charged groups raised in dissociation or ion adsorption. In turn, this effective charge could be used for the electrophoretic mobility or zeta-potential determination, if the particle diffusion coefficient is determined independently, and the system temperature is known. Another possibility is to separate particles with the same surface properties (i.e. zeta-potentials) but different sizes, where the sample selectivity is only due to the differences in diffusion coefficient. Of course, the real applications of ElFFF are defined by specific experimental conditions, opportunities and advantages rather than by method theory, but, without a clear physicochemical understanding of macromolecule and particle behaviour in ElFFF, the method applications will be very limited.

A focusing (or hyperlayer) mode of operation using isoelectric focusing in a pH gradient across the channel has been reported by a number of authors (see Further Reading) with a channel of trapezoidal cross section. However, the latter separation mode loses the high resolution characteristic for the FFF family due to high hydrodynamic dispersion interrelated to the shape of the cross section.

Limitations of Channel Configuration and Construction

Planar electrical FFF systems have been constructed, where the walls are defined by membranes permeable to the carrier liquid but not to the particles to be separated. In later versions these membranes are supported by porous or perforated plates. The membranes prevent the loss of the sample while allowing the passage of an electric current. Platinum wire electrodes lying outside the channel provide the transverse electric field. The carrier liquid represents a buffer, and a solution of identical composition is circulated through the chambers housing the electrodes in order to remove electrolysis products and reduce electrode polarization. Other configurations such as a hollow fibre systems and an annular porous glass channel have been reported. Presently, graphite or gold-plated glass channel walls are used, which minimize these effects. In a micro-machined channel for ElFFF, the electrode walls were of titanium and gold.

The resolution increases with the effective voltage drop across the channel, and increasing the applied voltage will have a positive effect on the resolution. Unfortunately, ElFFF is mainly carried out in aqueous solutions, and voltages above 1.7 V applied across the fluid-wall interface will cause significant electrolysis and bubble formation. Since the ElFFF system requires a stable flow velocity profile, bubbles cause serious flow disturbances, and electrolysis must be avoided. High flow velocities can limit the formation of bubbles and allow voltages above 1.7 V, but the available voltage is still small. Thus bubble formation in the electrochemical reactions at the wall electrodes is the limiting factor for the applied voltage.

Another voltage-related difficulty is the potential drop in the electric double layers near the channel walls. An electric double layer will cause most of the voltage drop to occur very close to the channel walls. As a consequence, the effective field which may be used for particle redistribution and separation, in the ElFFF system, is greatly reduced. Experimental data indicate that the effective field strength in the flow inside the channel is in the range of 0.25%–1% of the applied field depending on the composition of the buffer. Though this effect greatly reduces the performance of the ElFFF system, it is still able to perform separations. Due to the low electric field strength, Joule heating is not expected to be a significant problem in ElFFF, in contrast to electrophoresis systems.

One problem that arises in the separation in FFF systems is the symmetric parabolic velocity profile of the flow that performs the separation function. Indeed, particles with equal and opposite zeta-potential will elute at the same time from the channel. This can be a problem for samples containing both positively and negatively charged particles. Though such particles are usually prone to coagulation or aggregation, these processes may be slowed by a steric stabilization, for example, as in polyelectrolyte solutions or particles with adsorbed polymers. The coagulation or aggregation kinetics may then be studied by ElFFF. Most samples, and especially biological samples, are of a uniform charge type. Biological samples contain mostly negatively charged particles (at least the particles of interest). For samples containing both types of particle charge, the asymmetrical flow velocity profile and an additional particle velocity asymmetry may be arranged by the application of a longitudinal electric field in a channel having walls with different zeta-potentials, which can cause electroosmotic flow with a non-uniform velocity profile.

The establishment of Boltzmann equilibrium distribution in the channel requires a relaxation time for a particle to migrate from one channel wall to the other in the applied electric field. If the drift velocity U is constant, the relaxation time will be found using eqn [1]:

$$\tau_r = \frac{w}{U} \qquad [4]$$

In conventional ElFFF systems, the relaxation time typically is over 5 min, but in micro-machined ElFFF systems it may be less than 3 s.

ElFFF and Related Electrophoretic Methods

The nearest relatives of ElFFF are different electrophoresis techniques in liquids. However, electrophoresis systems often require very high field strengths for resolution, and the high voltages are limited by the Joule heating. Particle electrophoretic mobilities should also be high enough to have an acceptable resolution in common capillary lengths. Another type of electrophoresis separation system, free-flow electrophoresis, utilizes an electric field across a curtain of buffer between two vertical plates (a principle very close to FFF) and allows for continuous sample injection, but limits the detection and collection systems to the certain number of fractions. Resolution in free-flow electrophoresis is limited by fraction spreading in the fluid stream caused by the parabolic flow profile. Other methods of separating molecules and cells are needed for applications, where these limitations preclude the use of existing systems. Field flow fractionation is the solution for some applications, where particle electrophoretic mobilities are too low for the conventional electrophoresis systems and high electric field strengths are not desirable. ElFFF has all the advantages of FFF systems, i.e., the ability to separate cells, large molecules, colloids, emulsions, and structure, which are too delicate for electrophoretic separation such as liposomes, both in the 'original' condition and after surface modification. Unlike the free-flow electrophoresis systems, elution in FFF systems is zonal and proceeds through one outlet port; for this reason, it is capable of significantly higher resolution. Therefore, anticipated applications of ElFFF systems include cell separations, characterization of emulsions, liposomes, and other particulate vehicles for intravenous drug administration with respect to size, charge, and stability, diagnostic tests for specific molecules in colloidal suspensions, quick and accurate separations of molecules, environmental water monitoring, tests for sample contamination, and further research involving zeta-potentials. ElFFF systems also find application as sample pretreatment systems by performing an initial separation on a sample, which is later collected for further testing by another analysis system.

The resolution of ElFFF is determined in the standard way for chromatography, i.e. by the comparison of the sum of the peak dispersions for two neighbouring peaks to the difference of their maxima. The resolution of ElFFF is inversely proportional to the separation distance of the electrodes; thus, the smaller the distance between the channel walls, the higher the resolution between two distinct particles, making ElFFF an ideal application for using micro-machining techniques. The resolution increases with the square root of the channel length, so the longer the channel the better the resolution, but the time required for the improved resolution increases, which is not generally desirable.

Combined Electric-Thermal FFF (El-ThFFF)

An interesting combined technique represents the application of an electric field across the channel for Thermal FFF, where a temperature gradient is used to separate the analysed particles. After a potential drop of about 2 V is applied, the ThFFF retention is apparently changed. This combination allows a more exact examination of the particle surface properties, since ThFFF, like electrophoresis, represents a surface kinetic phenomenon defined by the surface force potential. Also, this combined FFF method gives information on particle electrokinetic properties in non-aqueous solution. El-ThFFF may allow distinction between electrostatic and non-electrostatic interactions in surface layer by programming of the electric field strength during the separation.

Conclusion

ElFFF is a method for the separation of charged particles and macromolecules according to their effective charge. This parameter is not measured by electrophoretic methods and may be obtained directly from ElFFF experiments. The effective charge may be used for the characterization of surface particle properties and macromolecule charged groups, when the required theory has been developed. ElFFF has electric field strength limitations due to electrochemical reactions at the channel walls and potential interface drop.

See also: **II/Particle Size Separation:** Field Flow Fractionation: Thermal; Theory and Instrumentation of Field Flow Fractionation.

Further Reading

Andreev VP and Ste panov YV (1997) Field flow fractionation with asymmetrical electroosmotic flow. II. Charged particles. *Journal of Liquid Chromatography & Relative Techniques* 20: 2873–2886.

Andreev VP, Stepanov YV and Giddings JC (1997) Field flow fractionation with asymmetrical electroosmotic flow. I. Charged particles. *Journal of Microcolumn Separations* 9(3): 163–168.

Caldwell KD and Gao Y-S (1993) Electrical field flow fractionation in particle separation. 1. Monodisperse standards. *Analytical Chemistry* 65: 1764–1772.

Caldwell KD, Kesner LF, Mayers MN and Giddings JC (1972) Electrical field flow fractionation of proteins. *Science* 176: 296–298.

Gale BK, Caldwell KD and Frazier AB (1998) A micromachined electrical field flow fractionation (μ-EFFF) system. *IEEE Transactions in Biomedical Engineering* 45(12): 1459–1468.

Giddings JC, Shiundu PM and Semenov SN (1995) Thermophoresis of metal particles in a liquid. *Journal of Colloidal Interface Science* 176: 454–458.

Liu G and Giddings JC (1991) Separation of particles in nonaqueous suspensions by thermal–electrical field flow fractionation. *Analytical Chemistry* 63(3): 296–299.

Martin M (1998) Theory of field flow fractionation. *Advances in Chromatography* 39: 1–138.

Martin M and Williams PS (1992) Theoretical basis of field flow fractionation. In: Dondi F and Guiochon G (eds) *Theoretical Advancement in Chromatography and Related Separation Techniques*, NATO ASI Series C: Mathematical and Physical Sciences, vol. 383, pp. 513–580. The Netherlands: Kluwer.

Schimpf ME, Russel DD and Lewis JK (1994) Separation of charged latex particles by electrical field flow fractionation. *Journal of Liquid Chromatography* 17: 3221–3238.