

Flow Injection Analysis

Flow injection analysis (FIA) is that type of continuous flow analysis that utilizes an analytical stream, unsegmented by air bubbles, into which highly reproducible volumes of sample are injected. Application of this principle to automatic analysis yields a fast, precise, accurate and extremely versatile system that is simple to operate.

The concept of flow injection analysis received earliest attention from the electrochemists. Nagy, Feher, and Pungor published their first in a series of papers describing injection of a sample into a flowing stream of electrolyte in 1970 (1). Their system involved passage of the sample carrier stream through a magnetically stirred mixing chamber followed by flow past a silicone-rubber-based graphite electrode. The resulting analytical readout was in the form of transient peaks.

Subsequently, Stewart, Beecher, and Hare in the U.S. (2) and Ruzicka and Hansen in Denmark (3) simultaneously modified the technique. Their primary innovation was in the use of flow-induced sample dispersion as the sample carrier stream was pumped through narrow bore tubing. This mechanism was used to effect controlled mixing of the sample with the stream as opposed to the gross mixing generated in the mechanically stirred chamber, thereby avoiding excessive sample dilution. As we shall see below, however, the mixing chamber also found application as their work proceeded.

The Danish group developed the method using primarily instrumentation normally associated with segmented flow analyzers (SFA). In contrast, the American group based their initial work on high-performance liquid chromatography (HPLC) components. This dichotomy in development technique emphasizes an interesting

Principles Techniques Applications Design

point about FIA: that it may be considered a hybrid of SFA and HPLC as described below.

The steadily increasing interest in FIA is evidenced by its inclusion as a separate section in such meetings as the American Chemical Society meeting (fall 1978) and the Pittsburgh Conference (spring 1980) as well as its major role at a flow analysis symposium held in Amsterdam (fall 1979) (4).

Betteridge's review (5) helped to stimulate interest in the United States. A useful introduction to early FIA theory together with an overview of FIA methods and techniques may be found in this publication. In addition, Ruzicka and Hansen have also reviewed FIA (6). Their most recent review included papers up to and including the flow analysis symposium.

The purpose of this paper is to summarize the concept of flow injection analysis by initially presenting a discussion of the basic principles and theories. In addition, the diverse techniques and applications developed to date for FIA will be reviewed. Finally, the design considerations for a flow injection analysis system will be presented.

In the past, the presence of the air

bubble in the analytical stream of a continuous flow system has been deemed necessary to effect three primary functions: (1) to limit sample dispersion; (2) to promote mixing of the sample with reagents by generating turbulent flow; and (3) to scrub the walls of the analytical conduits. Further study has shown that, not only are all of these functions possible in the unsegmented stream, but also that the absence of the air bubble actually expands the capabilities of the analytical system. The primary features of the unsegmented stream are: controllable sample dispersion; variable flow rates; baseline resolution between each sample; high sample throughput; and absence of any stabilization time. Figure 1 shows a generalized schematic for a fully automated flow injection analyzer. In practice, the standards and unknowns are loaded into the sampler which, operating in conjunction with the pump, aspirates the aliquots sequentially. As the samples are drawn up, reagents are simultaneously moved into the system by the pump. The samples are presented to an automatic injection valve where they are loaded. The valve is then switched and the analytical stream is directed through the valve to sweep out the sample.

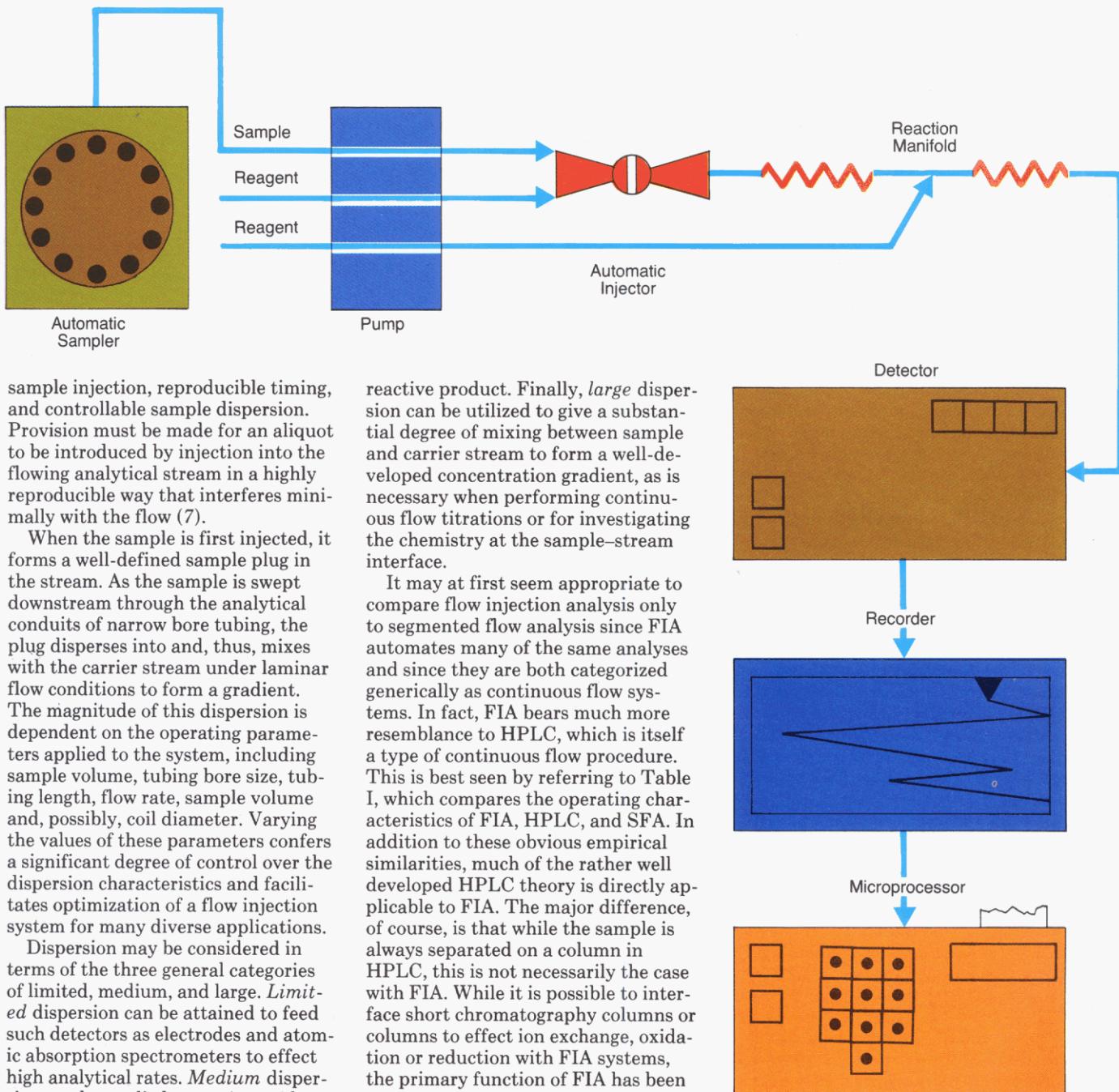
The sample and reagents move into the reaction manifold where the analytical processing occurs. Here, the sample may be reacted with a variable number of reagents, incubated, dialyzed, distilled or extracted. The reaction product is fed to the flow-through cell of an appropriate detector to generate an analog signal, which is directed to the recorder and microprocessor for data reduction. The results of a typical analysis are shown in Figure 2.

The technique of FIA is rigorous and depends on three primary factors:

Report

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sample injection, reproducible timing, and controllable sample dispersion. Provision must be made for an aliquot to be introduced by injection into the flowing analytical stream in a highly reproducible way that interferes minimally with the flow (7).

When the sample is first injected, it forms a well-defined sample plug in the stream. As the sample is swept downstream through the analytical conduits of narrow bore tubing, the plug disperses into and, thus, mixes with the carrier stream under laminar flow conditions to form a gradient. The magnitude of this dispersion is dependent on the operating parameters applied to the system, including sample volume, tubing bore size, tubing length, flow rate, sample volume and, possibly, coil diameter. Varying the values of these parameters confers a significant degree of control over the dispersion characteristics and facilitates optimization of a flow injection system for many diverse applications.

Dispersion may be considered in terms of the three general categories of limited, medium, and large. *Limited* dispersion can be attained to feed such detectors as electrodes and atomic absorption spectrometers to effect high analytical rates. *Medium* dispersion can be applied to attain a wide variety of reaction configurations to develop some detectable entity such as color, fluorescence or an electro-

reactive product. Finally, *large* dispersion can be utilized to give a substantial degree of mixing between sample and carrier stream to form a well-developed concentration gradient, as is necessary when performing continuous flow titrations or for investigating the chemistry at the sample-stream interface.

It may at first seem appropriate to compare flow injection analysis only to segmented flow analysis since FIA automates many of the same analyses and since they are both categorized generically as continuous flow systems. In fact, FIA bears much more resemblance to HPLC, which is itself a type of continuous flow procedure. This is best seen by referring to Table I, which compares the operating characteristics of FIA, HPLC, and SFA. In addition to these obvious empirical similarities, much of the rather well developed HPLC theory is directly applicable to FIA. The major difference, of course, is that while the sample is always separated on a column in HPLC, this is not necessarily the case with FIA. While it is possible to interface short chromatography columns or columns to effect ion exchange, oxidation or reduction with FIA systems, the primary function of FIA has been to automate wet chemical methods.

As this review proceeds, more similarities and possibilities for interface between FIA and HPLC will be en-

Figure 1. Generalized schematic of a fully automated flow injection analyzer

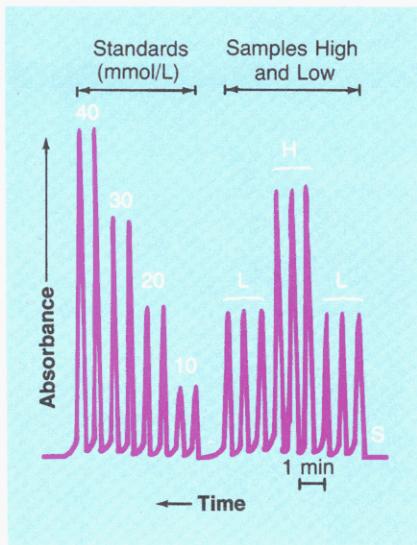


Figure 2. Typical FIA curves showing results from analysis of total CO_2 in plasma

Standards: 10–40 mmol/L. Samples: high (H) and low (L) in triplicate. S: injection point of first sample. Reprinted with permission from *Clinical Chemistry*, ref. 14.

countered. Not only does FIA operate on a mechanism similar to HPLC, which facilitates the use of comparable components, but its functions are complementary. Thus, FIA may serve as an automated precolumn sample treatment method or as a postcolumn derivatization or effluent storage system.

Principles

The most important parameter to control in FIA in order to ensure precision is the timing involved throughout the system. This demands particular attention to two parts of the physical system: the injection port and the pumping mechanism. The operation of the injection valve must be regulated to ensure injection of precise sample volumes. This feature precludes the requirement for reaching the steady-state, which is in contrast to the approach taken with segmented flow analyzers. It follows, then, that the residence time of the sample in the analytical conduits should ideally be identical for each sample, and the conditions to which the sample is exposed during processing should also be the same. Thus, the pump must be designed to generate reproducible flow rates to ensure precise sample residence times in the analytical manifold.

Before discussing the design considerations for a flow injection analyzer, the theoretical components of the concept should be understood. The fundamentals of the concept will be presented relative to experimental design for development of FIA methods.

Flow injection analysis systems have been described by Ruzicka and Hansen in terms of a series of mixing tanks (7) formed by four major system components: (1) the injection valve, (2) the flow cell, (3) the analytical conduits, and (4) linear and T-type connectors joining the components. Ideally, the injection valve and connectors should both have effectively zero dead volume while the flow cell will be of some fixed volume small enough to prevent its contributing significantly to the overall dispersion in the system. In this way, undesirable sample dispersion will be avoided and strictly controlled by varying the configuration of the analytical manifold.

The actual flow conditions obtained in FIA have been the subject of much investigation. While it was originally thought that turbulent flow is present (8), it was subsequently determined that FIA operates only in laminar flow regions (7, 9). In addition, the respective and combined effects of varying the operating parameters have been studied. Although this area has not been thoroughly described, some guidelines that assist in methods development work have been given by Ruzicka and Hansen (7). However, their work is based on the Taylor equations, the solutions for which are valid only for cases where either diffusion or convection is dominant in the dispersion process.

In reality, the flow conditions under which most FIA systems operate generate dispersion through both diffusion and convection. In this regard, Vanderslice et al. have demonstrated that flow injection systems can be described in terms of laminar flow equations (10). These relate to the diffusion-convection processes operating in the laminar flow region where FIA experiments are generally carried out. Specifically, the solutions of these equations give the travel time from injection valve to detector and baseline-to-baseline time duration which is a measure of dispersion. The equations are expressed in terms of the applica-

ble flow conditions and, thus, may be solved for any given set of operating parameters.

Of the several interesting principles derived from their work, perhaps most significant is the discovery that there is a critical set of flow conditions beyond which volume dispersion ceases to increase. This is in contrast to the statement by Ruzicka and Hansen, who assumed Taylor conditions, that dispersion increases with flow rate as the square root of residence time in the manifold *ad infinitum* (7).

The Vanderslice group also confirmed that it is radial rather than axial dispersion that contributes most significantly to sample dispersion in FIA systems. This type of dispersion, also called secondary flow (11), operates to move the fluid both toward and away from the tubing walls and thus serves as an efficient scrubbing mechanism. This concept is critical in understanding the low carryover and cross-contamination exhibited between samples processed in an unsegmented stream. Finally, secondary flow also serves to limit band spreading. Asymmetrical peak shapes are typically found in FIA skewed to the positive slope. Thus, some peak tailing is normally observed. Clearly, this band spreading has not prevented high sampling rates and low carryover and cross-contamination in FIA. However, maximum sampling rates cannot be realized unless the peak spreading is decreased. It has been demonstrated by Tijssen that this can be done, if required, using coiled capillary tubing together with pumping pressures and flow rates well within the practical range of FIA (11). Certainly, such small tubing diameters and, in fact, extremely high analysis rates are not of wide practical use currently, particularly in the laboratory encountering diverse sample materials containing particulate matter.

A more practical alternative to effect very high sampling rates has been suggested by van den Berg et al., whereby open narrow bore tubes are

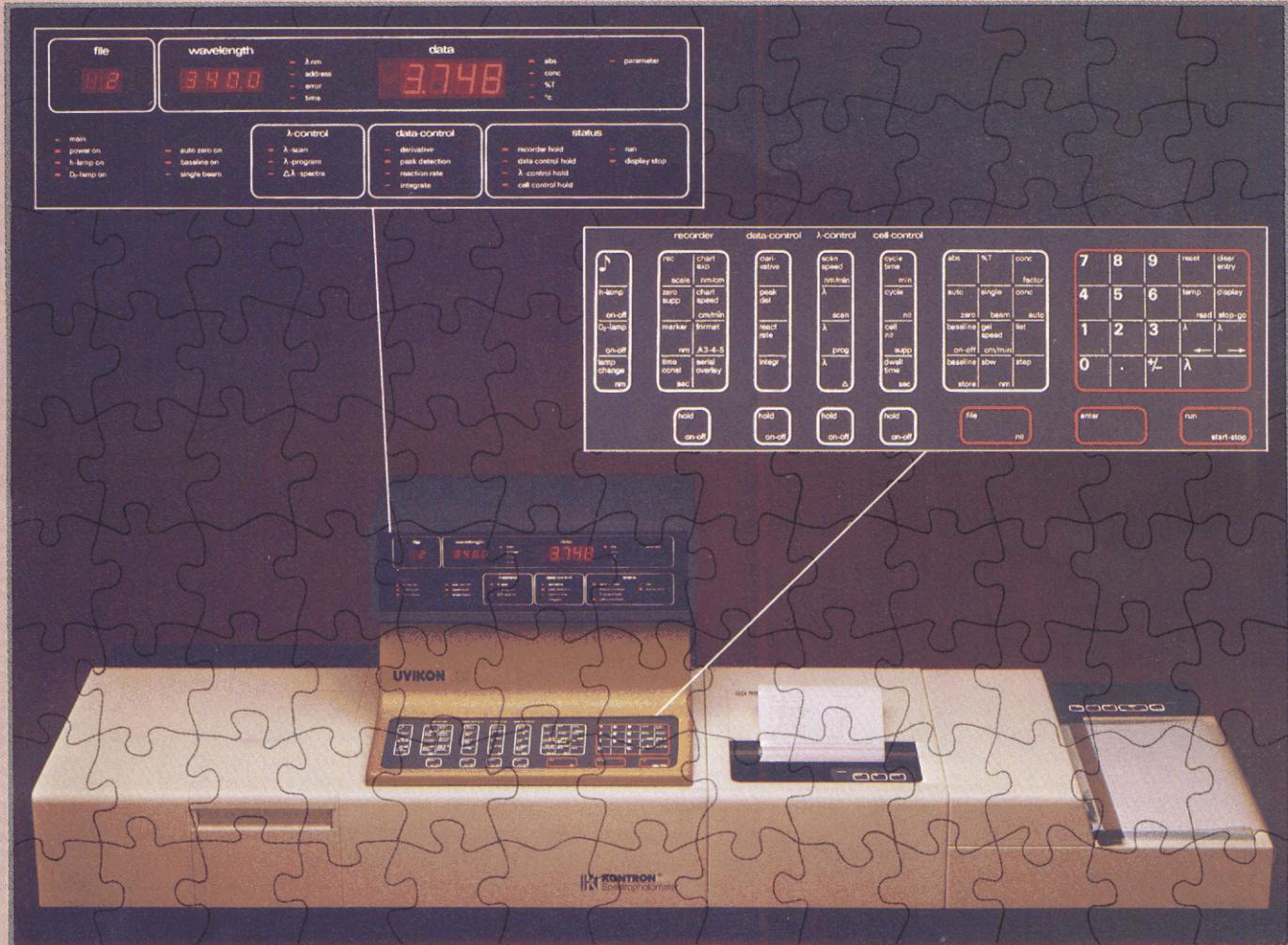
Table I: Comparison of Characteristics of FIA, HPLC and SFA

Parameter	FIA	HPLC	SFA
Sample introduction	Injection	Injection	Aspiration
Sample volume	Small (μL)	Small (μL)	Large (mL)
Analytical stream	Unsegmented	Unsegmented	Segmented
Manifold conduits	<1 mm i.d.	<1 mm i.d.	2 mm i.d.
Lag phase	Negligible	Negligible	Significant
Pump speed	Variable	Variable	Fixed
Pumping pressures	Low	High	Low
Column	Possible	Yes	Possible
Data reduction	Integration or peak height	Integration	Peak height

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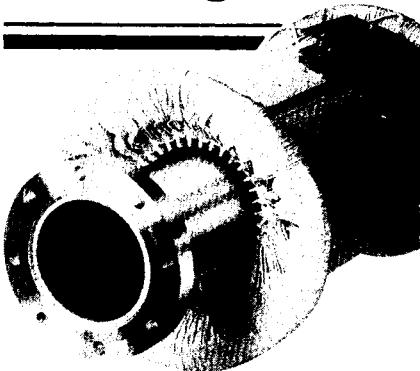
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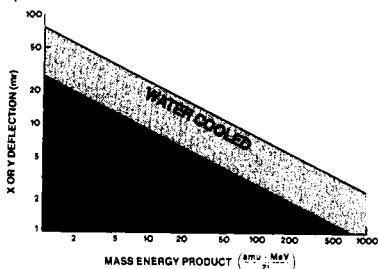


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replaced by packed bed reactors. With this approach, analytical rates of 500 samples per hour have been shown to be possible with low reagent consumption (12).

In developing a flow injection method, one of the primary goals is to maximize response together with sample throughput. In practice, this is done by determining the minimum length of tubing required for reaction by observing the effect of various lengths of tubing on the peak height or other response factors of interest such as linearity. It is obvious that in the single case where a dye is injected, an increase in dispersion will cause a decrease in peak height. However, in cases where a reaction is developed as a result of mixing effected by dispersion, the peak height will increase as the reaction proceeds toward completion. The maximum response will then be attained when an optimum balance is reached between dispersion and reaction time. Only when the decrease in response due to increased dispersion exceeds the increase in response due to reaction will the signal decrease.

Thus, in the design of real systems, it is desirable to determine the line length which gives the best response. However, because of variations in the volumes of given line lengths due to different bore sizes and deviations from manufacturers' specifications, a more appropriate parameter to help describe the system is mean residence time of the sample in the analytical manifold, that is, the post-injection valve (7).

As we have seen, FIA involves injection of highly reproducible sample volumes. This is unlike the aspiration approach taken in segmented flow analysis, which is a relatively imprecise sampling method causing sample volumes to vary as much as 3–4%. The fact that SFA procedures call for the reaction to be brought to the steady-state prevents the poor sampling technique combined with nonreproducible dispersion (13) from interfering with the overall precision of the system. In SFA, the reaction is brought to about 95% of completion, and the peak height is analytically significant. Varying amounts of sample and dispersion only serve to change the peak width and, to a very limited degree, peak height, since the reaction is proceeding so slowly at that point.

Precise sample injection, on the other hand, allows the reaction to be taken only to that point that yields satisfactory response, usually 75% of completion. Thus, the sample volume is essentially constant, varying less than 1%. This allows the analytical value to be taken from the area of the curve by integration, since the peak width will not vary significantly.

In general, the volume of sample used for analysis is chosen large enough so as to contain dilution below a 2:1 ratio. Since the first portion of the rising analytical curve is nearly linear, some fraction of that sample volume can be used as a straight-forward dilution technique for concentrated samples (7). This approach to sample dilution is superior to the introduction of a dilution loop since the latter only serves to lengthen the overall analytical line, thereby decreasing sample throughput. It follows then that any given manifold should be designed so as to minimize dispersion (for limited and medium dispersion systems) by using the shortest possible analytical line (7).

Techniques

One of the major benefits of continuous flow analysis as compared with other types of automated chemistry systems is its capability of performing sample pretreatment functions in-line. These serve primarily to remove interfering substances from the sample matrix or to place the analyte into some detectable form. The most important of these treatments include dialysis (liquid and gas), ion exchange, oxidation, reduction, solvent extraction and distillation. It has been demonstrated that FIA is capable of carrying out all of these processes.

Dialysis may be defined as the separation of small molecules from macromolecules by means of a semipermeable membrane. In FIA, thin film dialysis is used to isolate the species of interest from such interferences as proteins and fats. The dialyzer consists of two Lucite blocks with a precision semicircular channel cut into the inner surface. Typically, a cellophane dialysis membrane is placed between the blocks, the channels of which are aligned on either side of the membrane to form a single tube. In gas dialysis, the same physical system is used except that the membrane will be constructed of a gas-permeable substance such as silicone or Teflon.

The determination of CO₂ in plasma as performed by Baadenhuissen and Seuren-Jacobs is an example of gas dialysis (14). The sample is injected into a stream of H₂SO₄. This reaction releases CO₂, which permeates through a silicone membrane into a buffered cresol red indicator stream. Ninety samples per hour are analyzed with good precision and linearity.

Solvent extraction may be defined as the mechanical transfer of a solute between two immiscible phases. It is one of the most useful techniques available to effect sample separation, dissolution and concentration. As a result, the method has been adapted to flow injection analysis.

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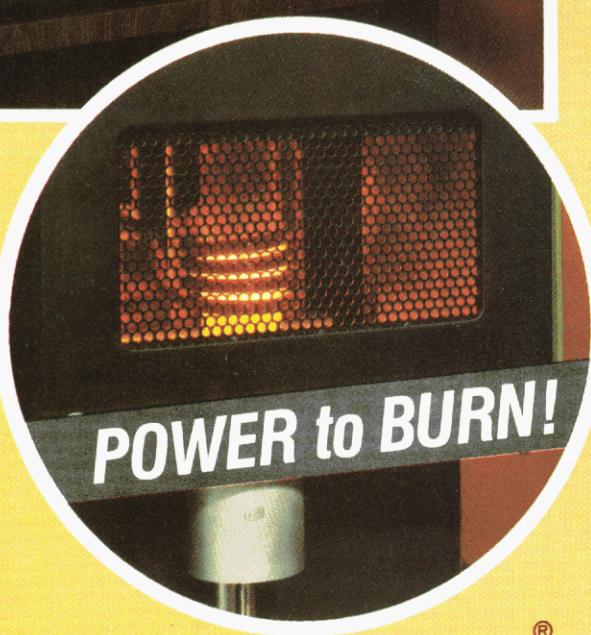


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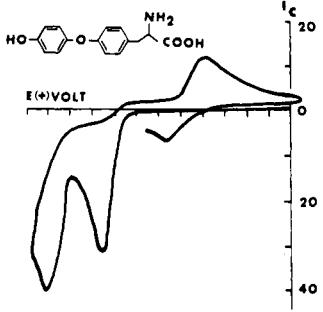
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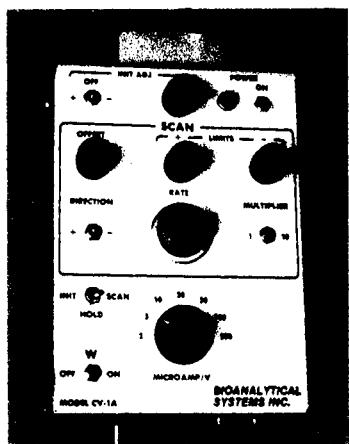


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Karlberg et al. originally designed the extraction apparatus to consist of a phase combination fitting (PC), extraction coil and phase separation (PS) fitting (15). The PC fitting consists of two inlets, one for each phase, consisting of a glass T-fitting. Two concentrically arranged lengths of Teflon tubing are inserted into the outlet of the fitting. By sliding the inner tube to change the distance between the edges of the two lengths, a regular mixing pattern and the lengths of the phase segments are established. So-called bolus flow is thus promoted in the extraction coil where the aqueous-organic interface is continuously refreshed, thereby providing a large surface area for rapid extraction. Furthermore, the emulsions often formed in manual extractions are avoided. The phase separation fitting consists of another T-fitting, one leg of which is Teflon-coated. The organic phase preferentially wets and thereby follows the Teflon route and, in conjunction with differential pumping, serves to effectively separate the phases.

An alternative system has been described by Kawase et al. (16). Here the PC fitting consists of two inlets located 45° relative to one another, which generates a regular alternating pattern of organic and aqueous phases. The PS fitting consists of a porous PTFE membrane, which is permeable to the organic phase but impermeable to the aqueous phase. This design appears to separate the phases more reliably than the Karlberg design.

A typical application for solvent extraction is in pharmaceutical product quality control. For example, over 70 samples of thiamine (vitamin B₁) can be determined per hour (17). Samples are injected into an aqueous stream of buffered potassium ferricyanide. This stream is then combined with chloroform to give alternating aqueous and organic segments to effect bolus flow through the extraction coil. The phases are then separated, and a portion of the organic stream is carried through the fluorimeter.

Column treatment has also been used successfully with FIA. The widely utilized cadmium reduction method for nitrate determination has been adapted, as have ion exchange columns, to remove interfering constituents from the sample. The manifold for nitrate determination involves the reduction of nitrate to nitrite and subsequent diazotization and coupling with the sulfanilamide/1-naphthylethylenediamine dihydrochloride reagent (18).

In addition to the above treatments, which can also be performed on segmented flow analyzers, albeit at a slower rate, there are several techniques unique to FIA.

The merging zones principle was developed by Bergamin et al. to minimize reagent consumption for those analyses where reagent may be expensive (19). In this operation, not only the sample, but also the reagent, are injected into carrier streams and directed to a confluence fitting. At that point, the two plugs meet, mix partially, and are carried through a reaction coil to promote further mixing. In this way, only enough reagent is introduced as is required by the particular chemistry, while the inexpensive carrier streams, typically distilled water, are used for washout.

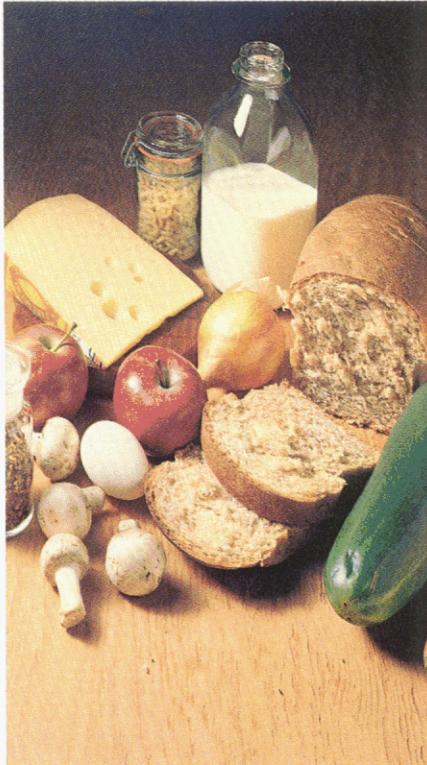
As was mentioned in the Principles section, sample dispersion decreases with flow rate. In fact, when the flow rate is zero, dispersion virtually ceases. This concept has been exploited for performing stopped-flow measurements to determine reaction rates using a single detector or simply to increase incubation time. Thus, enzymatic glucose determinations have been performed by Ruzicka and Hansen using stopped-flow combined with merging zones (20). The analytical rate is 100 samples per hour while reagent consumption is less than one unit of enzyme per sample.

Titrations can also be performed continuously by FIA, as demonstrated by Ruzicka et al. (21). In this case, the sample is injected into a carrier stream and fed to a mixing chamber to effect large dispersion. A well-formed concentration gradient is thus produced, which is directed to a confluence fitting where the sample mixes with titrant. The more concentrated the analyte, the sooner the end point will be reached as the sample and titrant merge. Thus, concentration is measured by length of the colored sample zone, which is reflected in peak width (Figure 3). The typical analytical rate for this method is 60 samples per hour.

Single point titrations have also been adapted to FIA by Astrom. Here the sample is injected into a stream of water, mixed with a linear acidic or basic buffer and delivered to a glass electrode for potentiometric detection, the peak height being analytically significant. Sample throughput is 180 per hour with a relative standard deviation of less than 1% (22).

In addition to titrations, sample gradients can be exploited for other purposes. Common problems with turbidimetric methods are poorly controlled crystal formations and accumulation of precipitate in the system, causing baseline drift and nonreproducibility. Baban et al. injected acidified samples containing sulfate into an analytical stream of alkaline barium chloride and EDTA. The turbidimetric reaction occurred within the acidified

What materials do you analyze?

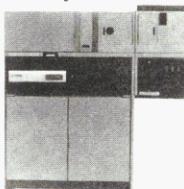


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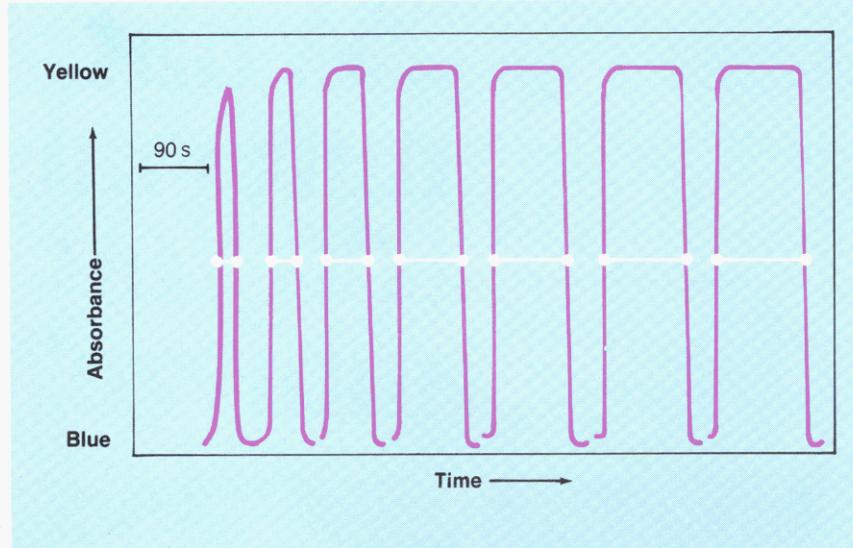


Figure 3. The colorimetric titration of a strong acid with a strong base in a one-channel manifold using bromothymol blue as indicator.

Sample concentrations, from left to right: 7×10^{-3} M; 1×10^{-2} M; 2×10^{-2} M; 4×10^{-2} M; 6×10^{-2} M; 8×10^{-2} M; and 1×10^{-1} M HCl. Reprinted with permission from *Analytical Chimica Acta*, 92, 246 (1977).

fied sample zone while the excess EDTA redissolved extraneous precipitate, thus effectively washing out the system between samples (23).

Applications

The medium dispersion capabilities of FIA have been applied to the colorimetric and fluorimetric analyses of many species. Methods have been developed incorporating as many as four reagents sequentially, as in the determination of ammoniacal nitrogen in animal feeds by Basson (24). Extended dwell times and sophisticated manifold designs are possible because, as discussed in the Principles section, the volume dispersion and, therefore, the dilution of the sample, can be maintained beneath an acceptable upper limit as required.

One of the many applications for FIA with limited dispersion is high speed feeding of such detection systems as flame atomic absorption and flame emission spectrometers [Wolf and Stewart (25)] and inductively coupled plasma spectrometers (26). Normally, under manual sampling conditions, an aliquot is aspirated into the nebulizer and a steady-state signal is attained. With FIA, an appropriate baseline reagent, typically deionized water, is constantly pumped through the nebulizer. The sample is periodically injected into this flowing stream and pumped through the nebulizer. In this way, transient signals are generated and sampling rates of up to 300 samples per hour can be realized. The principle of merging zones has been applied to this technique by Zagatto et al. to minimize the consumption of expensive masking reagent (lanthanum)

during analysis (27).

As is evident from the foregoing, FIA is capable of automating analytical procedures that previously demanded either manual attention or relatively complicated and expensive batch automation. Polarography, which has not been popular as a workhorse analytical tool in high volume labs, is such a technique. Both differential pulse polarography (DPP) and differential pulse anodic stripping voltammetry (DPASV) have been interfaced with FIA (28). In both cases, the sample is injected into the supporting electrolyte and pumped to a flow cell at the mercury electrode under limited dispersion conditions. For DPP, the continuously flowing stream is analyzed at the dropping mercury electrode. DPASV, on the other hand, involves plating from a flowing stream followed by pump stoppage and stripping analysis.

The sample and reagents may have to be deaerated depending on the analyte and the concentration level of interest. For low-level (low ppb) work and/or analytes having a half-wave potential near that of oxygen, an efficient in-line deaeration device has been designed (29). An alternative technique for substantially reducing oxygen interference has been the application of reverse pulse amperometry by Maitoza and Johnson (30).

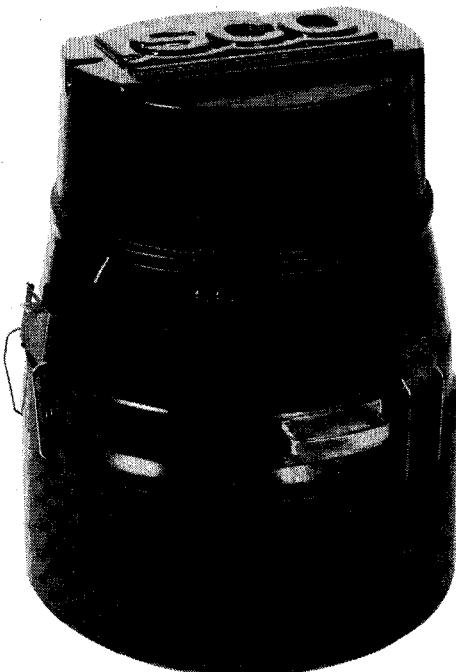
Amperometry at the reticulated vitreous carbon electrode has also been applied to FIA by Strohl and Curran to analyze several species (31). An example is the determination of epinephrine wherein samples are injected into a carrier stream of electrolyte consisting of 0.08M $\text{KH}_2\text{PO}_4/0.02\text{M}$

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K_2HPO_4 . Over 260 samples/h could be analyzed with a relative standard deviation of only $\pm 0.5\%$.

Stewart et al. have used an air gap electrode for potentiometric detection of ammonia (32). In this method, the sample is injected into a stream of sodium hydroxide. The ammonia gas subsequently evolved diffuses across the air gap to a pH-sensitive glass electrode to analyze about 100 samples/h.

Ramsing et al. have interfaced ion selective field effect transistors (ISFETs) with FIA to determine pH and potassium and calcium ions. The sampling rate and analytical precision are comparable to those obtained with ion selective electrodes (ISEs), but the reagent consumption is cut in half. In addition, the compactness of the system lends itself to substantial miniaturization and portability. Most significant, however, is the possibility of mounting multiple ISFETs in the same stream for multi-ion determination in a single sample (33).

A fast-evolving field itself, luminescence coupled with FIA forms a unique analytical system. Such a combination was used by Rule and Seitz in determining hydrogen peroxide. Here, samples were injected into an alkaline buffered stream containing luminol and copper (II) as a catalyst. The resulting light generated by the reaction was then read using a photomultiplier to analyze 360 samples per hour (34).

Differential kinetic analysis has been used with FIA to determine two species sequentially in a single sample. Kagenow and Jensen have determined magnesium, strontium, and calcium in this way by taking advantage of their different dissociation constants from the (2.2.2) cryptate complex (35).

Instrumentation

It has been seen that FIA has tremendous application in the busy laboratory where a workhorse system is required. In addition, FIA has a short start-up time and presents the first analytical readout generally within about 30 s following sample injection. Thus, it can also be used for analyzing only a few samples. Finally, by taking advantage of the various types of dispersion, many different types of analyses can be performed.

The final design of a flow injection analyzer is dependent on the particular requirements of the user. However, critical to the successful operation of a flow injection analyzer is the thoughtful design of the analytical manifold. Since sample dispersion is being used to effect specific functions including sample mixing, reaction, and dilution, it should be controlled as meticulously as possible. Thus, the manifold should consist not only of the sample treat-

ment components (holding coils, heating blocks, extraction apparatus, etc.), but also the injection valve at the inlet and the detection device as close to the outlet as possible. In addition, fittings used to interconnect the various manifold components and modules should be well made. These basic design rules serve to minimize fixed system dead volume.

Many types of valve designs have been incorporated in flow injection systems to perform sample injection, such as rotary, solenoid and slider valves. For most applications, the various approaches seem to be comparable in capability. The primary considerations in choosing a valve for a particular application are smooth injection, compatibility of wetted surfaces with sample and stream components, and accommodation of the required injection volume.

As was mentioned above, for many applications the steady-state is not attained in FIA. Therefore, since the reaction is being monitored on the exponentially rising portion of the curve, it is vital that the sample be treated in a reproducible manner following the injection valve to ensure accuracy and precision. It is the pumping mechanism that serves to mediate the residence time of the sample in the manifold. Therefore, this unit must be designed to deliver reproducible flow rates. For this application various pump types have been used, including syringe, peristaltic, progressive cavity, and single and dual piston pumps. In addition, constant head pressure has been used. Once again, application dictates choice of approach. For moving corrosive fluids, the peristaltic approach is probably the least desirable. On the other hand, for pumping aqueous fluids a peristaltic pump will provide the lowest cost per channel. However, in this respect it should be emphasized that fewer pumping channels are used for a particular analysis in FIA as compared with SFA. The constant head approach may be desirable where absolute economy is required, but it will be relatively inflexible.

The most basic components of an FIA system having been considered, there are three additional modules that should be mentioned. First, the detector. As is obvious from the foregoing review on applications, many different types of detectors have been applied to FIA. In general, any detector that can be equipped with a flow-through cell is a candidate for interfacing with FIA.

For use of the FIA as a workhorse in a busy analytical laboratory an automatic sampler is most desirable. Since flow injection can perform as a high speed analytical system, the sampling apparatus should be capable of accom-

modating relatively large batch sizes. This minimizes the operator attention required to change sample trays.

Finally, in this advanced age of electronics, a microprocessor can also be interfaced economically. This can be used to increase the ease of use of the system by generating user interaction messages for operating program input and to control the functioning of the system using the operator-specified parameter values. Furthermore, data reduction can be fully automated using microprocessor technology. Such functions as integration, linearization, baseline drift correction, and function monitoring can all be performed automatically and the analytical results printed out in an organized format (36, 37).

In summary, the role of flow injection analysis in the scientific community is broadly defined. Significantly, it offers an alternative to segmented flow analysis. It is appropriate for both laboratory and on-line applications. Furthermore, as we have seen, its capabilities are extremely diverse. Not only can it serve as a dependable workhorse system, but it can also automate difficult analyses, function as a research tool and, due to the short time between injection and readout, give prompt results for just a few samples. The exponential increase in FIA publications (albeit mostly of European origin) since 1977 testifies to some of the innovative possibilities that exist for the technique, and this trend should continue for several years to come.

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Author's Note: While space has precluded the inclusion of all papers currently published concerning flow injection analysis, a complete bibliography is available from the author.



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