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Electroosmotic pumps for microflow analysis

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Abstract

With rapid development in microflow analysis, electroosmotic pumps are receiving increasing attention. Compared to other micropumps, electroosmotic pumps have several unique features. For example, they are bi-directional, can generate constant and pulse-free flows with flow rates well suited to microanalytical systems, and can be readily integrated with lab-on-chip devices. The magnitude and the direction of flow of an electroosmotic pump can be changed instantly. In addition, electroosmotic pumps have no moving parts. In this article, we discuss common features, introduce fabrication technologies and highlight applications of electroosmotic pumps.

Keywords

Constant flow; Electroosmosis; Electroosmotic flow; Electroosmotic pump; Lab-on-chip; Microanalytical system; Microchip pump; Micropump; Microflow analysis; Pulse-free flow

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1. Introduction

Integration and automation of multiple analytical processes and miniaturization of analytical instruments have been active research areas in the past half-century. Traditionally, chemical assays were implemented using a batch approach.

The first autoanalyzer, an air-segmented flow instrument, was developed in the late 1950s [1] and was improved in the early 1960s [2]. Air bubbles had been an issue in this instrument.

In the mid-1970s, a flow-injection (FI) technique was invented [3] and that eliminated air bubbles in the flow stream. Following FI, a sequential-injection (SI) method [4] was developed in the early 1990s. In the early 2000s, a lab-on-valve (LOV) device was developed [5] and was recently reviewed [6].

In the above systems, various "tubings" were used as conduits to transfer sample and reagent solutions, as chambers to perform chemical reactions, and as flow cells to facilitate detection. Since the early 1990s, a microfluidic or lab-on-chip (LOC) device has emerged as a new platform to integrate analytical processes and miniaturize analytical instruments [7]. In LOC devices, the various tubings were microfabricated into chips using standard photolithographic technologies developed in the semiconductor industry. To miniaturize FI, SI and LOV systems or to enable LOC devices to perform FI and SI analysis, micropumps are needed to manipulate solutions within the fluidic networks. Many micropumps have been developed and were reviewed recently [8].

In this article, we review a special class of micro pumps – electroosmotic pumps (EOPs).

2. Unique features

EOPs use electroosmosis or electroosmotic flow (EOF) to drive liquids around within fluidic conduits. EOF is the movement of uncharged liquid relative to a stationary charged surface due to the application of an externally electric field [9]. It is a phenomenon inherent to a solid-liquid interface [10]. In 1809, Reuss [11] had discovered the phenomenon of electroosmosis, wherein the application of an electric field across a porous dielectric material caused liquid to flow. Using EOF to drive liquid for chemical analysis was pioneered by Pretorius et al. [12]. Although Theeuwes had developed EOPs for controlled drug delivery in 1975 [13], they were not popular in analytical chemistry until the 1990s, when they were applied in miniaturized analytical systems [14–17].

Compared with other pumps used in micro-analytical systems, EOPs have several unique features:

1. EOPs are bi-directional and their flow directions can be switched almost instantly. This feature comes from the nature of EOF. By changing the polarity of the electric field, the direction of EOF can be switched instantly. This property enables EOPs to perform rapid, accurate manipulations of solutions, critically important in studying fast chemical reactions on the microscale (e.g., ~10-μm channel).
2. EOPs are capable of generating constant and pulse-free flows. This is essential to microscale flow analysis, although minute flow-rate fluctuations (pulsed flows) are tolerable in regular FI/SI systems in which the conduits often have dimensions > 200 μm.
3. EOPs can be readily integrated with LOC platforms, due to the common materials and processes involved in the production of both devices. This is crucial to integrated

microfluidic systems when multiple-step chemical analysis is performed. Piezoelectric and silicone-membrane-based micropumps [18,19] can be fabricated on LOC platforms, but their versatility, reliability and accuracy are inadequate for high-quality analytical applications (e.g., pipetting nL solutions) [20].

4. EOPs have no moving parts. The moving parts in all mechanical pumps are usually lifetime-limiting components and sources of inaccuracies and failures. EOPs eliminate such components.

These are a few primary advantages of EOPs. Table 1 presents a comparison between an EOP and other common types of pumps used in microflow analysis. One inherent issue associated with EOPs is contamination of pumping elements by pump solutions, especially when a system solution is used as the pump solution.

3. Fabrication

Based on the types of pumping elements used, EOPs can be categorized as open channel, packed column, monolith column and porous membrane. The following introduces the processes employed in making these pumps.

3.1. Open channel

In open-channel EOPs, both silica capillaries and microchannels on chips have been used as the pumping elements.

Fig. 1 presents an EOP made from an open capillary [14]. The pumping element was a segment of a bare fused silica capillary (C1). A and B were two reservoirs holding a buffer (e.g., sodium tetraborate) solution. The reagent holding coil (HC) was a piece of capillary tubing filled with the reagent solution to be delivered. V1 was a selection valve.

When the valve was set at the position as shown in Fig. 1, the two syringes (S1 and S2) were isolated from the pump system. As the valve was switched to another position, S1 connected to C1, and S2 connected to HC. C1 could be rinsed with the solution in S1, and HC could be replenished with the reagent in S2. HV was a high-voltage power supply. A key component of this EOP was the grounding joint, which separated the pumping element (C1) from the chemical-reaction system (HC and the fluidic network after HC). It was constructed using a piece of Nafion ion-exchange-membrane tubing (M).

Fig. 2 shows a detailed construction of this joint. When C1 and connection capillary were joined, a small gap was left between them. Two PVC-tubing sleeves were used to secure and to seal M to C1 and the connection capillary. This membrane joint allowed electrical connectivity through ion conduction between the solutions inside and outside the membrane tubing, but solutions could not flow across the membrane. V1 was normally set to join the connection capillary and HC, as shown in Fig. 1. When a negative high voltage was applied, pump solution flowed backwards, which allowed the free end of the capillary to aspirate solutions. When a positive high voltage was applied, pump solution flowed forward to propel the solutions in HC to the rest of the fluidic network.

The pump rate can be controlled by adjusting the electric field strength applied to C1. Alternatively, the pump rate can be boosted by employing parallel pumping capillaries. To construct a multiplexed-capillary EOP, a union is required to combine all the outlets of the capillaries into one outlet. Making such a union with small dead volumes was an issue for open-capillary EOPs [15–17]. This issue can be easily addressed using microfabrication technologies.

Fig. 3 shows an example of an open-channel EOP [21]. The pumping element was a group of shallow microfabricated channels called pumping channels (1). All pumping channels had a common inlet (2) and outlet (3) reservoir. The pumping element was exposed only to buffer solutions and did not come into contact with the sample solution. A porous glass disk (5-mm diameter, 0.8–1-mm width, and 4–5-nm pore size) was utilized to facilitate application of the electric field between reservoirs 2 and 3, and also to prevent EOF leakage to reservoir 3. Reservoir 3 was fabricated from a PEEK external nut, and the porous glass disk was secured at the bottom of reservoir 3 with a corresponding internal nut. As a positive electric field was applied between reservoirs 2 and 3, EOF was generated to propel the solution(s) downstream.

The pumping elements in open-channel EOPs were usually produced using standard photolithographic technologies [22].

3.2. Packed column

Packed columns are commonly used as pumping elements in EOPs, which are normally capable of producing higher flow rates than open-channel EOPs due to their increased porosities. When fine particles are used, the pore diameters become very small and hence high pumping pressures can be achieved (e.g., 8000 psi [23]).

The methods for producing packed columns for EOPs are identical to those for packing columns in capillary LC or capillary electrochromatography. The first step is to create a short (e.g., 1 mm) frit close to one end of the capillary (e.g., [24]) by introducing a cohesive paste made up of one part sodium silicate solution (14% NaOH aqueous solution) and three parts non-porous silica particles, then baking the capillary in an oven at 350°C for 20 min. In the second step, a non-porous silica bead slurry is pressurized into the capillary using a slurry packing apparatus. In the final step, after the beads are densely packed inside the column, a second frit is fabricated near the open end of the capillary by sintering. Such a column, with the two frits retaining the beads inside it, constitutes a packed-column EOP.

The overall configuration of a packed-column EOP is similar to that of an open-channel EOP except for the grounding joint. In packed-column EOPs, the grounding joint is often made from a metal electrode directly in contact with the pump solution (e.g., [25]) albeit porous columns have been used [26]. This configuration encounters a problem (i.e. gas bubbles generated from the electrolysis are trapped inside the fluidic system). A porous Teflon membrane device has been employed to release these bubbles [25]. Alternatively, platinum (catalyst) can be used to recombine H_2 and O_2 into H_2O [27].

3.3. Porous monolith

Microporous monolithic columns are outstanding options as pumping elements for in manufacturing EOPs. A porous polymer monolith is a single, continuous piece of highly cross-linked porous polymer that can be prepared by a simple polymerization process from liquid precursors, including monomers, cross-linker, free radical initiator and porogenic solvents. The polymer completely fills the volume of a specifically-designed chamber or a section of a capillary or a microchannel. An excellent feature of the monolithic column is the elimination of frits. The monolithic materials used for EOP development can be polymer-based or silica-based [28,29].

Silica monoliths are frequently used for development of EOPs. The following presents a typical procedure for preparing the monolith [30]. The inner surface of a capillary was first cleaned and activated by washing the capillary with NaOH, HCl, water, acetone and diethyl ether. A monolithic silica matrix, comprising 0.5 mL of 0.01 M acetic acid, 54 mg of poly(ethylene glycol) and 0.2 mL of tetramethoxysilane, was introduced into an appropriate length of the

capillary. The ends of the capillary were then connected with a Teflon tube to form a loop and placed in an oven at 40 °C for 24 h. After the silica gel made within the capillary was washed with water and 0.2 M ammonium hydroxide, the columns were placed into the 40°C oven for another 24 h. The column was heated in a temperature programmable oven at 80°C, 120°C, 180°C, and 300°C for 4 h at each temperature, purged with helium at 180°C for 1 h, and cooled to room temperature at the rate of −1.0°C/min. Other protocols have also been used to produce silica monolith [31,32].

A potential problem for silica monolith is that silica can be dissolved slowly in alkaline solutions. This dissolution will change the structure of the monolith and hence the EO flow rate. In the worst cases, the monolith will collapse. An organic polymer monolith will overcome this problem.

Detailed methods for making polymer monolith have been described [33,34]. The following protocol presents an example for making a monolithic column with an average pore size of ~1 μm. The inner wall of a capillary was first derivatized with 3-(trimethoxysilyl)propyl methacrylate. A polymerizing solution, containing 1.2 g of 75% 2-(methacryloyloxy)ethyl] trimethylammonium chloride in water, 0.3 g ethylene dimethacrylate, 1.96 g 1-propanol, 0.84 g 1,4-butanediol, 0.15 g water and 13 mg azo(bisisobutyronitrile), was then introduced into the capillary. This capillary, with both ends sealed by silicone septa, was submerged in a water bath at 55–60°C for polymerization for ~24 h. After the monolith was flushed with methanol to remove all unreacted components, a monolithic column was produced. The pore dimension of the monolith can be tuned over a broad range (0.01–10 μm) by controlling the amount of the porogenic solvent, the percentage of cross-linking monomer in the polymerization mixture, and the polymerization temperature [35,36].

3.4. Porous membrane

Porous membranes (porous frits are categorized as a special kinds of porous membrane) have also been used as the pumping element in EOPs. A unique feature of these materials is that they provide high-density arrays of short pumping channels. This feature leads to low-voltage EOPs, because the short pumping channels enable application of a low voltage to produce a high electric field across the pumping element.

Porous membranes are often commercially available (e.g., glass frit [27], ion exchange membrane [37], and silica and alumina membranes [38]). These materials can also be prepared in laboratories. For example [39], a porous membrane can be produced by putting a layer of polysilicon film onto a porous silicon template using an oxidized, low-temperature, chemical-vapor-deposition process. The pores go straight across the template, and are distributed hexagonally with diameters of the order of 6 μm and pitch distances of 8.5 μm [39]. Because the polysilicon film grows on the entire surface of the template, the final pore size can be controlled by controlling the thickness of the polysilicon. These membranes have an advantage over porous glass frits in that the porous silicon tortuosity approaches unity. Porous frits can also be produced via a sintering process [40].

Porous-membrane EOPs are configured the same way as the packed-column EOPs. However, because the membranes or the frits are short, a sandwich structure is frequently used to support the pumping element [27,37–39].

4. Applications

4.1. Microflow-injection analysis (μ-FIA)

To demonstrate EOPs for FI applications, Dasgupta and Liu [14] constructed a two-line FI system for chloride determination. Referring to Fig. 4, there were two EOPs similar to that

described in Fig. 1, but each pump comprised four single open-capillary (40 cm × 75 μm i.d. × 375 μm o.d.) pumps in order to increase the flow rate. The pump electrolyte (2 mM sodium tetraborate) was used directly as the carrier stream in which the sample was injected via V2 (100-nL injection volume), so no holding coil was necessary in this line. A holding coil, HC, was used in the reagent [0.8 mM $Hg(SCN)_2$ and 0.2 M $Fe(NO_3)_3$] line.

The chemistry behind this method involved a reaction between chloride and mercuric thiocyanate, forming mercuric chloride and releasing thiocyanate. The released thiocyanate reacted with ferric ion in the same solution, forming a blood-red complex that could be detected by an absorbance detector.

In this system, the flow rate of each pump was ~1.7 μL/min. A good linear relationship was obtained for Cl^- determination ($R^2 = 0.996$ for 50–600 ppm [Cl^-]), with a relative standard deviation of ≤0.8% (n = 13).

A similar EOP has also been used for SI analysis of nitrite-nitrogen and ammonia-nitrogen [16]. Fig. 5 presents the configuration of the SI system. The HC is a capillary holding coil with a length of 40 cm and an inner diameter of 250 μm. The EOP was connected to the common port of a selection valve (V2), which was pneumatically operated.

The Griess-Saltzman reactions [41] were employed for nitrite-nitrogen analysis and the nitroprusside-catalyzed Berthelot reaction [42] was utilized for ammonia-nitrogen determinations. This application took advantage of an EOP capable of instantly switching flow direction. Excellent linear relationships ($R^2 = 1.000$) were obtained for both nitrite-nitrogen (20–400 μM) and ammonia-nitrogen (50–600 μM).

Pu and Liu [22] manufactured an EOP on a microchip and demonstrated its application for an enzyme-inhibition assay. Fig. 6A shows the photomask design of the pump chip and Fig. 6B the SI system. The microchip EOP contained a pumping element of 32 parallel channels, each with a depth of 20 μm and a total length of ~27 cm. An isolation channel was also fabricated on the chip to separate the sample and reagent solutions from the pumping solution. The isolation channel served as a sample and reagent holding coil as well as for the SI analysis. The experimental set-up was identical to a conventional SI system except for the microchip EOP. The system was applied to β-galactosidase-catalyzed hydrolysis of fluorescein di(β-D-galactoside) and inhibition of this hydrolysis reaction by diethylenetriaminepentaacetic acid.

There were three basic steps to accomplish the assay:

1. a negative high voltage was applied to the EOP to aspirate sample and reagents into the isolation channel;
2. after the sample and reagents were reacted adequately, a positive high voltage was applied to the pump to propel the product to the detector for measurement; and,
3. the system was reset (this included washing the sampling capillary attached to the selection valve and loading this capillary with the next sample solution).

For either of the above SI systems, if the EOP was replaced with a syringe pump, the reproducibility would deteriorate considerably because syringe pumps cannot control flows that precisely.

4.2. Microfluidic liquid chromatography (μ-LC)

EOPs offer a simple, cost-effective means to generate adequate pressures and flow rates for capillary or chip-based liquid chromatographic (LC) separations. Paul et al. [43] constructed a high-performance LC (HPLC) system using a packed-column EOP. The pump column (0.15

mm i.d. and 3 cm long) was packed with 1.5-μm diameter non-porous silica beads, and the separation column (0.1 mm i.d. and 11 cm long) was packed with 3-μm diameter octadecylsilane-coated porous silica beads. Separations of polycyclic aromatic hydrocarbons were performed on this system.

Chen et al. [25] built an EOP capable of generating pressures in excess of 3 MPa and flow rates in the μL/min range. The pump comprised three parallel fused-silica capillary columns (25 cm × 530 μm i.d.) packed with 2-μm silica beads. Hollow metal tubes were used as grounding electrodes. Fig. 7 shows the one-stage EOP and the μ-HPLC system. The μ-HPLC system comprised a four-port injection valve with a internal loop of 200 nL, 15 cm × 320 μm i.d. 5 μm Spherigel C_{18} stainless-steel analytical column and an on-column ultraviolet-visible (UV-Vis) detector.

To evaluate the performance of the system, a mixture of thiourea, benzene, toluene, naphthalene, phenanthrene, biphenyl and anthracene were separated. Acetonitrile/water was used as the mobile phase. The number of theoretical plates of the column was $2.3–3.2\times10^4$/m using the EOP, and $1.4–2.3\times10^4$/m using a mechanical pump. The retention-time (t_r) error expressed in RSD% was within 0.8% with the EOP for all compounds tested, while the t_r error was 3.6% with the mechanical pump.

Lazar et al. [44] developed a microfluidic HPLC system (Fig. 8) for protein analysis. The system comprised two EOPs, a valving component, a separation channel with an on-column preconcentrator, and an electrospray ionization (ESI) interface. The separation channel (5) was 2 cm long and 50 μm deep. The packing material comprised 5-μm Zorbax SB-C18 particles, loaded manually in the channel from the LC waste reservoir (11) using a syringe. The packing material was retained in the separation channel with microfabricated multi-channel filter structures (~100 μm in length and ~1.5–1.8 μm in depth). The two EOPs (1A and 1B) were identical, and each comprised 200 nano-channels (2 cm long, ~1.5–1.8 μm deep). The voltage for EOF generation in the pumps was applied to reservoirs 2A/2B and 3. The voltage applied to reservoir 3 was also the voltage for generating the electrospray. EOF leakage from outlet reservoir 3 was prevented by a porous glass disk (5-mm diameter, 0.8–1-mm width, 40–50-Å pore size), which was secured to the bottom of the reservoir. Sample loading was accomplished through a double-T injector (4) via the EOF valving structures (8 and 9), each comprising 100 nano-channels (2 cm long, ~1.5–1.8 μm deep). As the hydraulic resistances of the EOPs and the valving structure are much larger than that of the separation channel, the parallel channels act as a valve that is open to material transport when an electric field is applied and closed to material transport when the electric field is removed. A fused-silica capillary (10 mm long, 20 μm i.d. and ~90 μm o.d.) was inserted into the LC channel (5) for generating the electrospray (10). The flow rates generated were sufficiently stable for nano-LC separations with detection by mass spectrometry (MS). The analysis enabled confident identification of 77 proteins.

For HPLC applications, piston pumps may be utilized, although they are difficult to integrate into microfluidic chip devices.

Table 2 summarizes the applications of EOPs in microflow analysis.

4.3. Other applications

EOPs have been used for other applications.

Jin et al. [53] reported a proteolytic digestion chamber on a microchip. Various solutions were electroosmotically transported to the chamber, and the peptide products were subsequently analyzed using capillary electrophoresis (CE) and matrix-assisted laser desorption/ionization

time-of-flight MS (MALDI-TOF-MS). The digestion results from this microchip device were comparable to those from a conventional water-bath digestion apparatus.

Dasgupta and Liu [54] connected an EOP to the detection end of a CE capillary to control the flow pattern in the CE capillary. The majority of CE applications involve samples having lower ionic strength than that of the running electrolyte to achieve sample stacking. In such cases, the auxiliary EOP can be used to optimize the stacking profile and thus improve the separation efficiencies.

EOPs have also been used in micro-energy systems. In particular, EOPs have been utilized for water management in proton-exchange-membrane (PEM) fuel cells [55] and for methanol/water-mixture delivery in direct methanol fuel cells (DMFCs) [56]. Kim et al. [56] described the use of an EOP made of porous glass to deliver methanol/water for a DMFC, and Buie et al. [57] developed a miniature, convection-free DMFC that utilized a planar EOP for methanol delivery to the anode. EOPs have also been used for cooling electronic devices [58].

5. Conclusion

EOPs have been demonstrated to be efficient for fluid propulsion and aspiration. They can be used in FI, SI, LOV and LOC systems. EOPs can generate stable, pulse-free flows from a few nL/min to several mL/min. Generally, if high pump rates are utilized, maximum pumping pressure will be sacrificed. This may not be of concern, because typically a high-flow-rate FI/SI system has relatively low flow resistance, unless a packed-bed reactor or a filtration system is used. The most important features of an EOP are that it can propel and aspirate solutions, it can generate pulseless, stable flow, its flow rate and direction can be changed instantly, it has no moving parts, and it can be readily integrated with microfluidic and microelectromechanical system (MEMS) devices. EOF pumps are ideally suited to microfluidic systems for which pulseless, stable flow is desired.

Flow stability in an EO pumped system has been a problem in some applications, because solutions of different compositions go through the capillaries. Sometimes, flow rates change because of the adsorption of compounds from the samples or sample matrix onto the surfaces of the pumping elements. This problem can be avoided if the pump fluid is separated from the sample and reagent solutions in the analytical system. When properly designed, EOPs can be used as a stand-alone pump or integrated into a microchip device to generate adequate flow rates and pressures for development of miniaturized HPLC.

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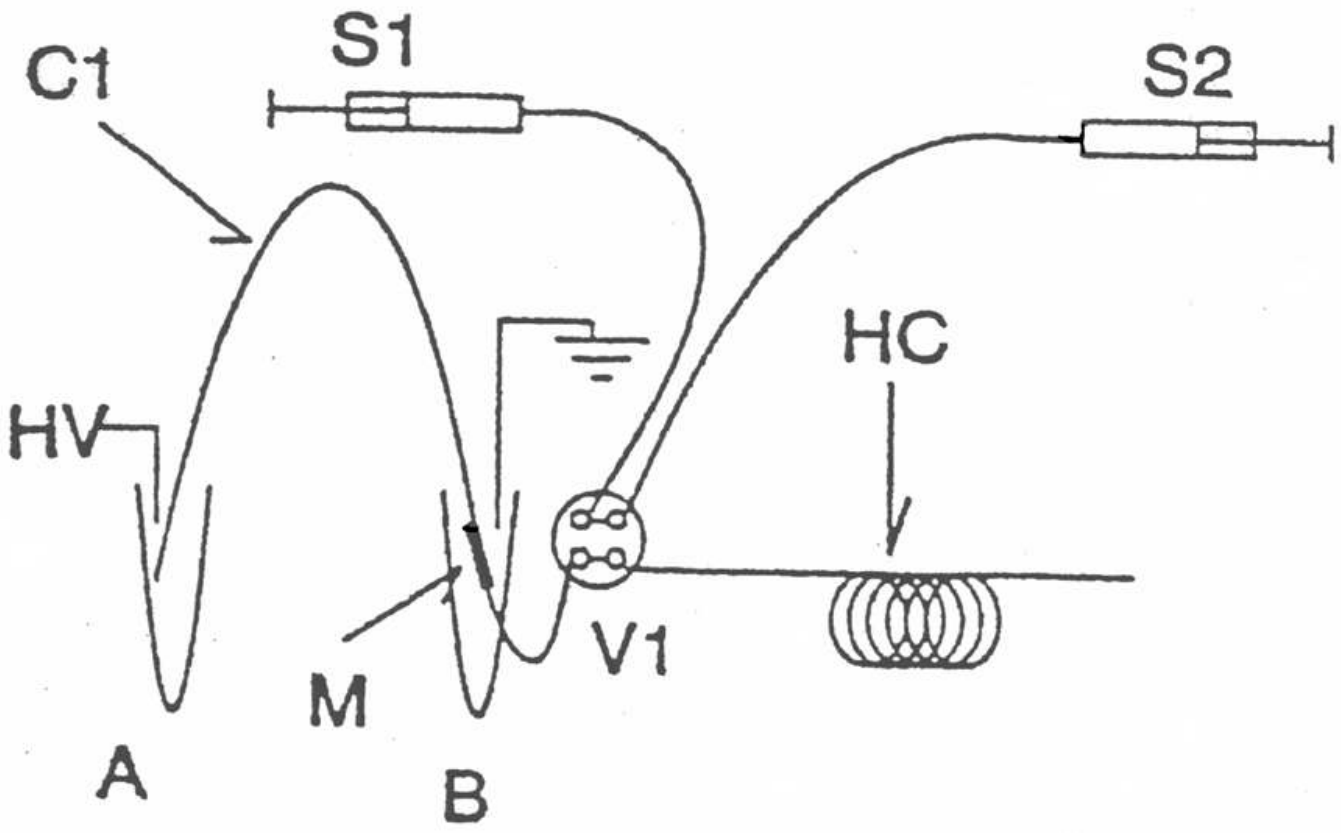

Figure 1.
Stand-alone electroosmotic pump (Reprinted with permission from [14]).

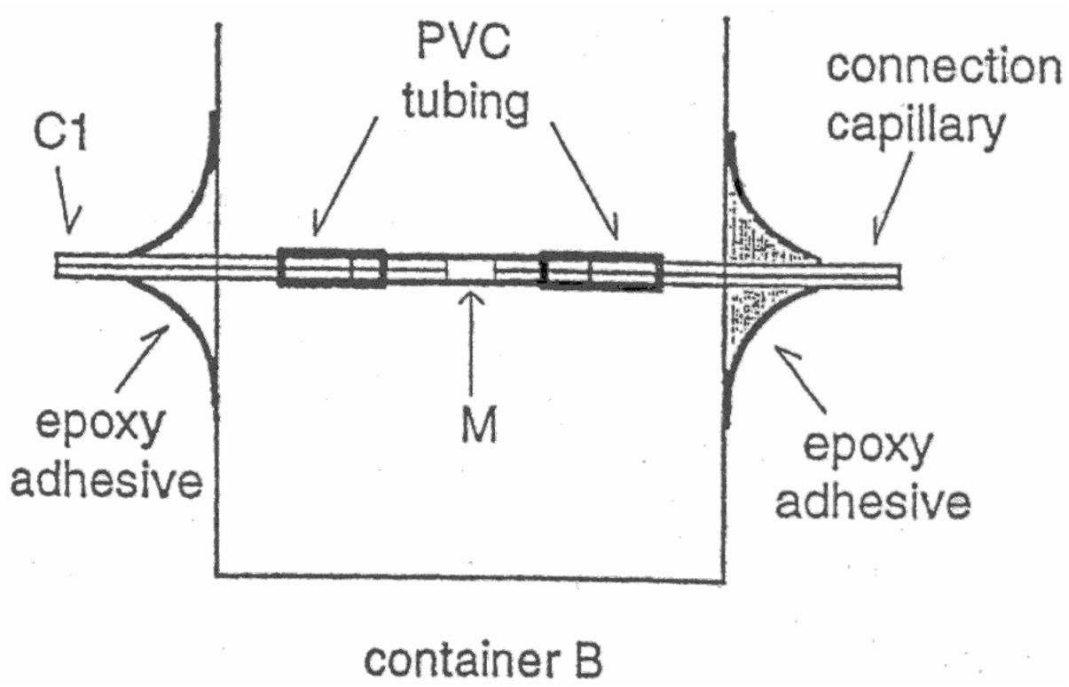

Figure 2.
Membrane joint (Reprinted with permission from [14]).

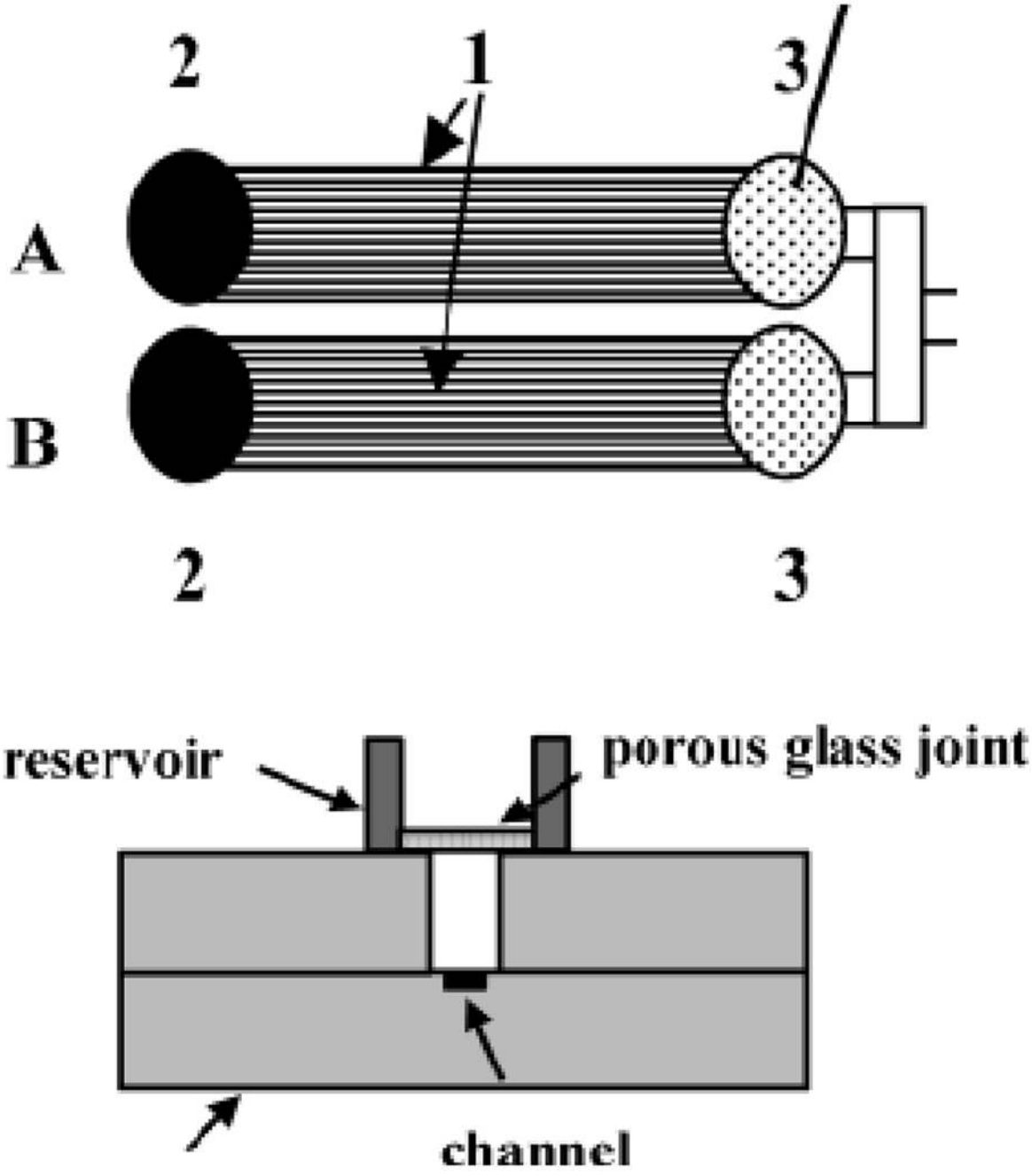

Figure 3.
Open-channel electroosmotic pump (EOP). 1 – Open-channel EOP, 2 – Micropump inlet reservoir, and 3 – Micropump outlet reservoir. The bottom figure shows an expanded view of reservoir 3 containing the porous glass disk. (Reprinted with permission from [21]).

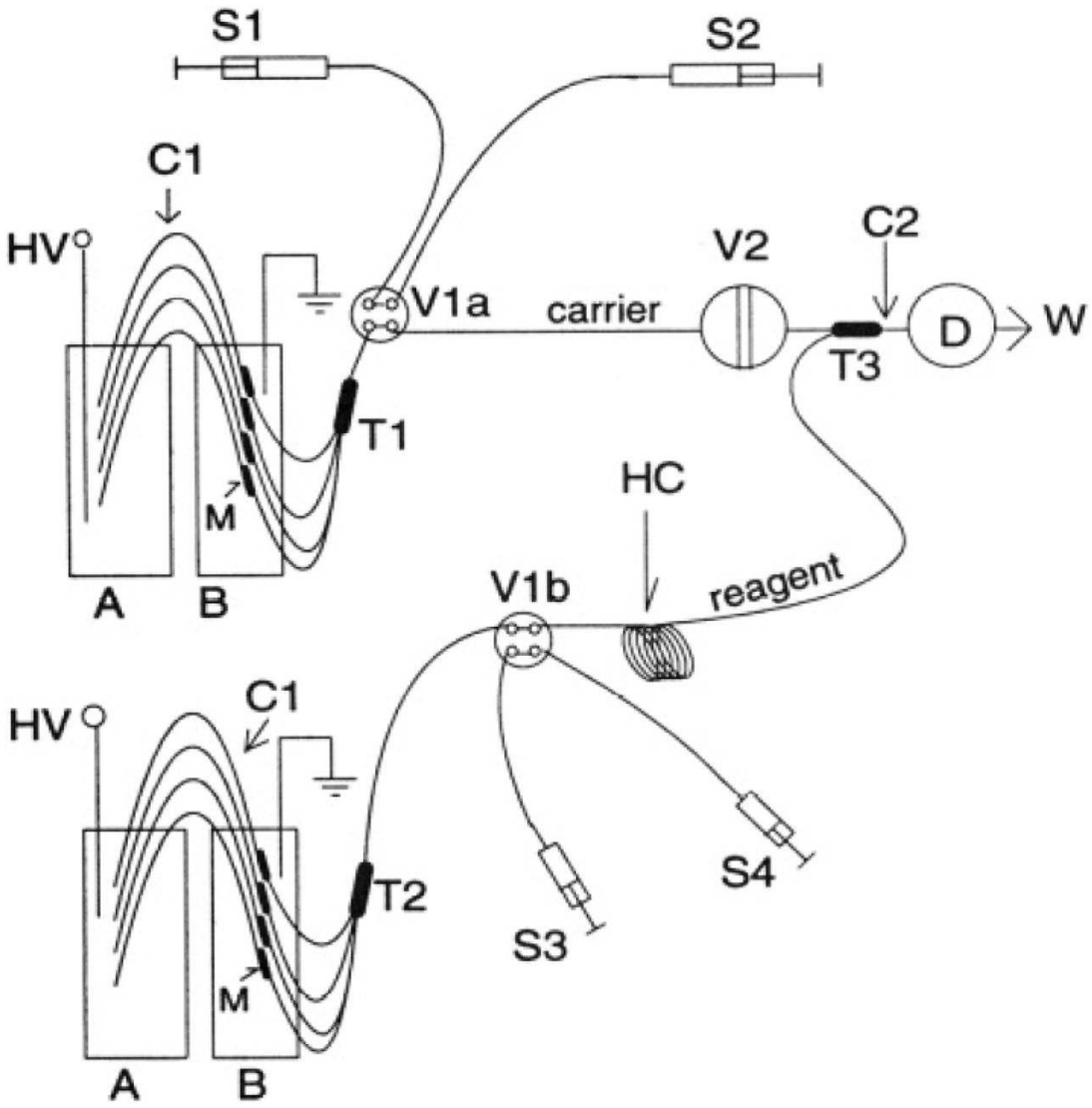

Figure 4.

Two-line flow-injection analysis (FIA) system with electroosmotic flow (EOF) pumping: B, Pump electrolyte-solution container; T1, T2, Capillary unions; Vla and Vlb, Four-way valve stacks a and b; S1 and S3, Syringes holding pump-buffer solution; S2 and S4, Syringes holding carrier and reagent solutions, respectively; HC, Reagent holding coil; T3, Low-volume tee union (Reprinted with permission from [14]).

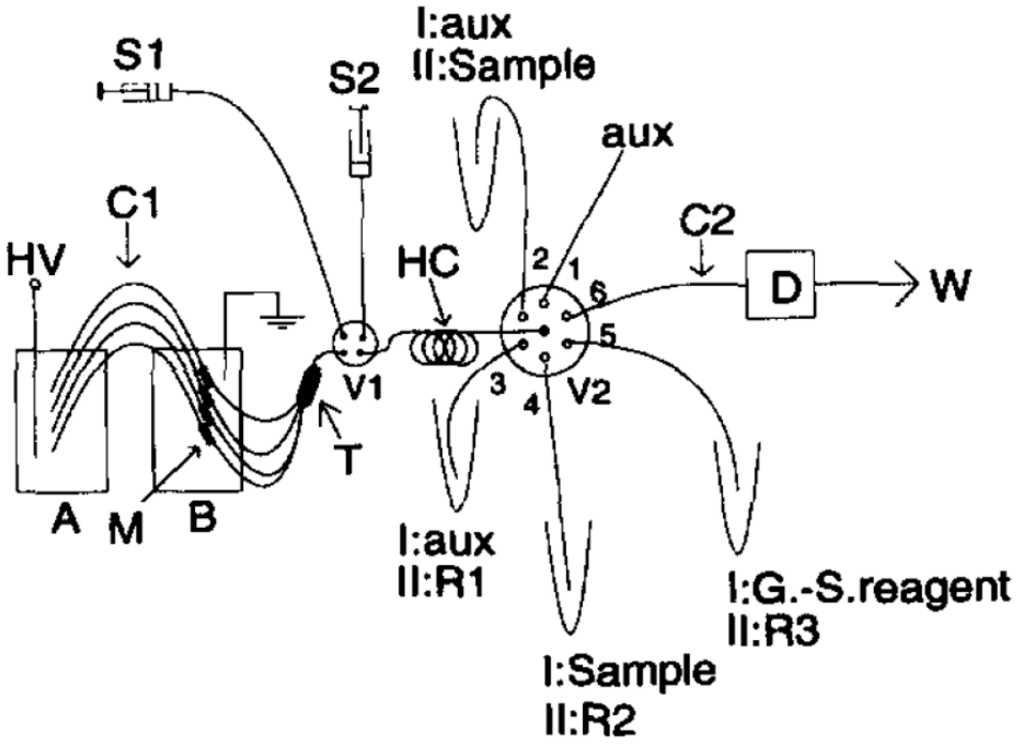

Figure 5.
Capillary-format sequential injection analysis (SIA) system. HV, High-voltage power supply; A, B, Pumping electrolyte-solution containers; M, Membrane joint; Cl, Pumping capillary; T, 4 x 1 union; HC, Holding coil; Vl, Four-way valve; Sl and S2, Syringes; V2, 6 x 1 selector valve; RI, R2, R3, Reagents; aux, Unused auxiliary solution port (Reprinted with permission from [16])

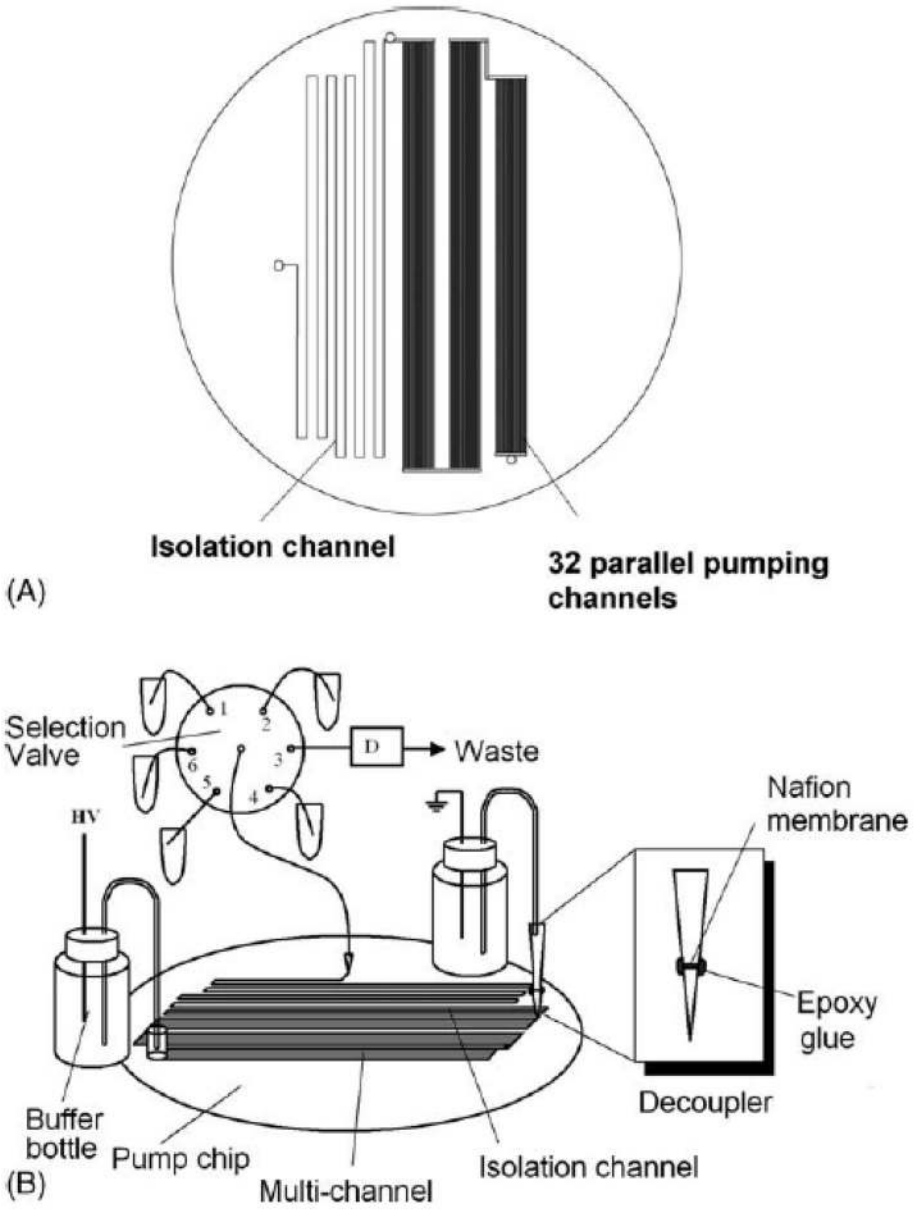

Figure 6.
(A) Photomask design of the pump chip. (B) Micro-electroosmotic pump-sequential injection analysis (μ-EOP-SIA) system (Reprinted with permission from [22]).

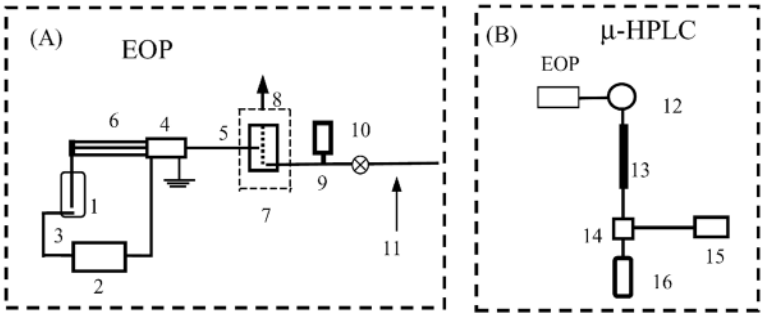

Figure 7.

One-stage electroosmotic pump (EOP) and the micro high-performance liquid chromatography (μ-HPLC) system. (A) The EOP system: 1, Solvent reservoir, covered with an insulating sheath; 2, High-voltage direct-current source module; 3, Pt wire; 4, Hollow electrode (grounded); 5, Capillary conduit; 6, Packed columns, three packed columns connected in parallel; 7, Gas-releasing device; 8, Representation of direction of gas flow); 9, Liquid-pressure sensor; 10, Open/close valve; 11, Measurement point of flow rate. (B) The μ-HPLC system: 12, Four-port injection valve; 13, Analytical capillary HPLC column; 14, On-column ultraviolet-visible (UV-Vis) detector; 15, Chromatographic data station; 16, Waste-liquid bottle (Reprinted with permission from [25]).

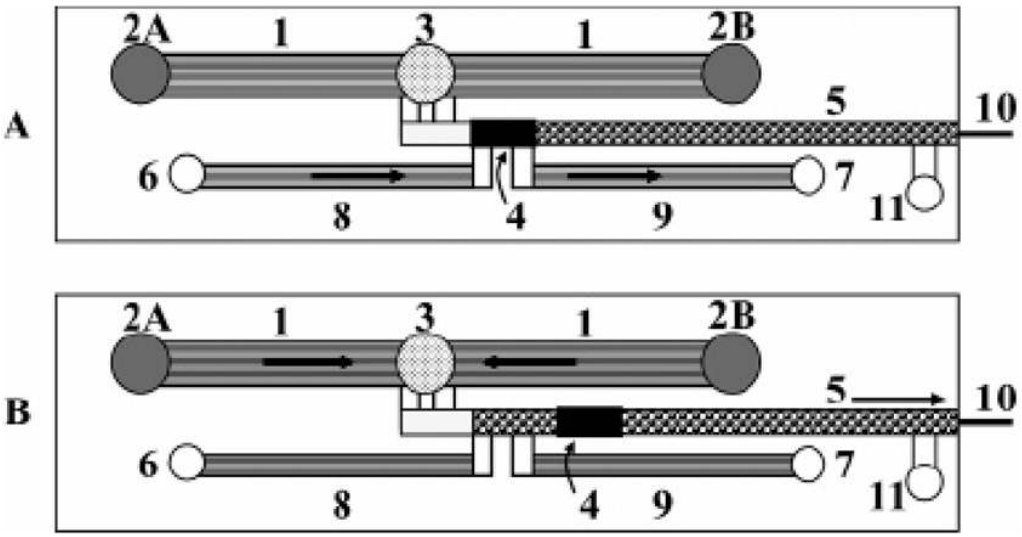

Figure 8.
(A) Photomask design of the pump chip. (B) Micro-electroosmotic pump-sequential injection analysis (μ-EOP-SIA) system (Reprinted with permission from [44]).

Table 1

Function comparison between electrosmotic pumps (EOPs) and other common pumps in microflow analysis

		Pump features										Compatibility			
		Propulsion	**Aspiration**	**Pulse-free flow**	**Pumping pressure**	**Flow controllability**	**Flow control accuracy**	**Microfabrication compatibility**	**No moving parts**	**Durability/ lifetime**	**Free of pump contamination**	**Flow injection**	**Sequential injection**	**Lab-on-a-valve**	**Lab-on-a-chip**
EOP	***Open channel***	V[a]	V	E	V	E	E	E	E	E	P	V	V	V	E
	Packed column	E	V	E	E	E	E	G	E	E	P	V	V	V	E
	Monolith column	E	V	E	E	E	E	V	E	E	P	V	V	V	E
	Porous membrane	V	V	E	G	V	V	G	E	E	P	G	G	G	E
Piezoelectric pump		V	P	F	F	G	F	E	G	V	G	G	P	P	F
Silicone membrane pump [18,19]		V	G	P	F	G	G	G	G	G	V	G	F	F	G
Syringe pump		E	E	V	V	G	G	P	G	V	E	E	G	G	G
Pressurized container		E	P	E	V	P	P	G	V	E	E	F	P	P	F
Peristaltic pump		E	F	P	F	P	P	F	P	G	V	E	F	F	P
Piston pump[b]		E	P	P	E	F	F	P	F	V	V	V	F	F	P

[a] The rating is based on the following scale (from the best to the worst): E (excellent), V (very good), G (good), F (fair) and P (poor).

[b] This pump represents reciprocal high-pressure HPLC pumps.

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Table 2

Summary of EOP applications in microflow analysis

EOP type	Pumping element	Pumping solution	Flow rate	Pumping pressure	Application	Dynamic range or concentration utilized	Detection limit	Ref.
Open channel	60 cm long × 75 μm i.d. capillary	**1** 10 mM NBu_4ClO_4 & 20 mM 1,10-phenanthroline (pH 4.9) **2** 5 mM 2-[bis(2-hydroxyethyl) aminoethane sulfonic acid and 25 mM NBu_4ClO_4	n.a.[c]	n.a.	μFIA for Fe^{2+}	5–200 mg/L with a RSD of 2.9%	n.a.	[45]
Open channel	Four parallel 40 cm long ×75 μm i.d. capillaries	2 mM $Na_2B_4O_7$	~nL/min to 100 μL/min	n.a.	μFIA for Cl^-	50–600 ppm with a RSD of ≤ 0.8%	n.a.	[14]
Open channel	Four parallel 40 cm long ×75 μm i.d. capillaries	2 mM $Na_2B_4O_7$	n.a.	n.a.	μFIA for nitrite and ammonia	20–400 μM for nitrite & 50–600 μM for ammonia	n.a.	[16]
Open channel	32 parallel 89 cm long ×100 μm wide × 20 μm deep microchannels	2 mM $Na_2B_4O_7$	5 μL/min	n.a.	μFIA for enzyme inhibition assay	n.a.	n.a.	[22]
Open channel	200 μm i.d capillaries	10 mM acetic acid/10% methanol, 65% acetonitrile/ 10 mM acetic acid	~nL/min	n.a.	μHPLC-MS for peptides	n.a.	1 fmol or100 nM	[46]
Open channel	200 parallel 2 cm long × 7–10 μm wide × 1.5–1.8 μm deep microchannels	15 mM NH_4HCO_3 in H_2O/ CH_3OH (40:60), pH~8	10–400 nL/min	100–200 psi	μHPLC-MS for proteins, 77 proteins identified.	n.a.	n.a.	[44]
Open channel	Six parallel 83 mm long ×300 μm wide × 50 μm deep microchannels	10 mM borax	1.25 μL/min	n.a.	Nanotitration for Fe^{2+}	8 mM Fe(II) sample	n.a.	[47]
Open channel	4–50 mm long × 11–20 μm wide × 1–6 μm deep microchannel	15.4 mM NH_4HCO_3/CH_3OH	10–400 nL/min	Up to 80 psi	ESI-MS for bovine hemoglobin digest	2 μM	n.a.	[21]
Packed-column	3 cm × 0.15 mm i.d. capillary packed with	25% MeCN/5 mM pH 7.5 phosphate buffer	5 mL/min at 150 psi	10 psi/V	μHPLC for polycyclic aromatic hydrocarbons	n.a.	n.a.	[43]

EOP type	Pumping element	Pumping solution	Flow rate	Pumping pressure	Application	Dynamic range or concentration utilized	Detection limit	Ref.
	1.5μm i.d. non-porous silica beads							
Packed-column	Three parallel capillaries (25 cm × 530 μm i.d.) packed with 2 μm silica beads	Methanol/water	nL/min to a few μL/min	Above 5.0 MPa at 20 kV	μHPLC	0.1 mM thiourea, 0.3 mM benzene, 0.2 mM toluene, 0.2 mM naphthalene, 0.2 mM phenanthrene, 0.2 mM biphenyl, and 0.3 mM anthracene	n.a.	[25]
Packed-column	Three parallel capillaries (25 cm × 530 μm i.d.) packed with 2 μm silica beads	Acetonitrile/water	a few μL/min	>3.0 MPa at 9 kV	μHPLC for thiourea, naphthalene, phenanthrene, and anthracene	n.a.	n.a.	[48]
Porous membrane	2–5 μm pore glass disc (13 mm thick & 35 mm in diameter)	0.35 mM NH_4OH	3 mL/min at 500 V	0.15 MPa at 500 V	μFIA for Cr(VI)	0–7.0 mg/L with a RSD of 0.4%	n.a.	[49]
Porous membrane	Porous glass	0.5 mM diethanolamine	1.35 mL/min at 500 V	n.a.	μFIA for Cr(VI), Pb(II)	0.2–40 μg/L	10 ng/L Cr13 ng/L Pb	[50]
Porous membrane	Porous glass	0.1 mM trithanolamine	2 mL/min at500 V		μFIA for nitrite	10–800 μg/L	1 μg/L	[51]
Porous monolith	100 μm i.d. and 6 cm long silica monolith	0.26 mM Tris/1.5 mM EDTA buffer, pH 6.0	200 nL–2.5μL/min	0.4 Mpa at 6 kV	μFIA for dopamine	0.1 mM dopamine	n.a.	[31]
Porous monolith	Silica monolith	2 mM NaCl	400 nL/min at 2 kV		μFIA for Ca^{2+}	10 μM Ca^{2+}	40 μg/L	[52]

[c] n.a. stands for “not applicable” or “not available”.