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Journal of Chromatography A, 1057 (2004) 247–251

JOURNAL OF CHROMATOGRAPHY A

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Short communication

Improvement of heat dissipation for polydimethylsiloxane microchip electrophoresis

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Received 6 July 2004; received in revised form 19 August 2004; accepted 1 September 2004

Abstract

Effective removing of Joule heat in polymer-based microchip system is an important factor for high efficient separation because of lower heat conductivity of polymers than silica or glass. In this paper, a new kind of polydimethylsiloxane (PDMS) microchip electrophoresis system integrated with a laser-induced fluorescence detector has been successfully constructed on the basis of a commercial heat sink for computer CPU (central processor unit). Experimental results on separation current using high concentration running buffers demonstrated that heat dissipation of PDMS/PDMS microchip system was significantly improved. Furthermore, with this integrated system, theoretical plate number of fluorescein using 100 mM phosphate-buffered saline + 1 mM sodium dodecyl sulfate as running buffer was determined to be 2750 (for 2.5-cm separation channel, corresponding to 110,000/m). This high separation efficiency demonstrated that such heat sink-based polymer microchip system could be effectively applied for high-concentration buffers.

Keywords: Heat sink; Polydimethylsiloxane; Capillary electrophoresis; Microchip; Laser-induced fluorescence; Joule heat; Instrumentation

1. Introduction

When high voltage is applied in electrokinetic separation systems, Joule heat would be inevitably generated. Generally speaking, Joule heat would influence many physical properties of the solution such as temperature, viscosity etc, and then separation efficiency of the electrokinetic system [1,2]. Some approaches have been studied to improve the heat dissipation in capillary electrophoresis from the sides of experiments [2,3] and theories [4,5]. Because the increased internal temperature is distributed radically in the capillary for silica or glass microchip electrophoresis, it has been reported that the influence of Joule heat on the separation efficiency has been greatly reduced due to the larger ratio of surface to volume of the microchannels [6–8]. Due to high cost and long period of manufacture for silica or glass microchips, polymers such as polydimethylsiloxane (PDMS) have been introduced into microchip production [9]. But dissipation of Joule heat would become much more difficult because such polymers have much poorer thermal conductivity than silica or glass [10,11]. For PDMS microchips, Li and co-workers have theoretically simulated and experimentally observed that the maximum internal temperature in the PDMS/PDMS microchips would be up to 58 °C while in PDMS/glass hybrid ones, this temperature was only 32 °C under the same conditions [11]. Furthermore, in order to improve the separation efficiency or to extend application of electrophoresis, it would be better to use higher concentration running buffers [12] or micellar electrokinetic chromatography [13]. The higher concentration running buffer or micelles will inevitably increase the electric conductivity and then the internal temperature, so that it would be much more difficult for their application in polymer microchips.

To the best of our knowledge, improvement to eliminate the influence of Joule heat in polymer microchip system has not been reported. Recently, with the fast development of

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doi:10.1016/j.chroma.2004.09.009

computer hardware, heat sinks for central processing unit of personal computer have been successfully commercialized to remove large amount of heat that is generated when the computer is running. Such commercial devices provide a good approach to create a convenient platform for improving the heat dissipation of polymer microchip electrophoresis easily. Here, we report such a platform for PDMS microchip electrophoresis integrated with laser-induced fluorescence detection. Heat dissipation of such a system using running buffers with high concentration was investigated by comparison with normal system. Separation efficiency for this integrated system was also primarily investigated through electrophoresis of fluorescein using high-concentration running buffers.

2. Experimental

All reagents were of analytical grade. Fluorescein and sodium dodecyl sulfate (SDS) were purchased from Fluka (Buchs, Switzerland). Na_2HPO_4 and KH_2PO_4 were purchased from Nanjing Chemical Reagents Factory (Nanjing, China). All solutions were prepared with doubly distilled water and passed through a 0.22 μm cellulose acetate filter (Xinya Purification Factory, Shanghai, China).

2.1. Instrumentation

2.1.1. Heat sink basis

The heat sink with a fan (model: PAL8045T) for computer CPU (central processor unit) was from Alpha Co. (Japan) [14]. Its thermal resistance is 0.32 °C/W, which represents high efficiency for heat dissipation. Its surface is embedded with copper, and the effective area for heat dissipation is 42 mm long and 42 mm wide. In four holes bored on the heat sink, four Pt electrodes were fixed with glue. These four electrodes were used to perform sample injection and separation (shown in Fig. 1B–E). The mixture of PDMS monomer and curing agent was directly coated on heat sink and then was put into the oven for 1.5 h under 65 °C. The thickness of PDMS substrate should be as thin as possible so that Joule heat can be effectively dissipated. But too thin PDMS substrate would suffer from being broken down by separation voltage [15]. Under our experimental conditions, the PDMS substrate with thickness of ca. 500 μm was tested to be suitable.

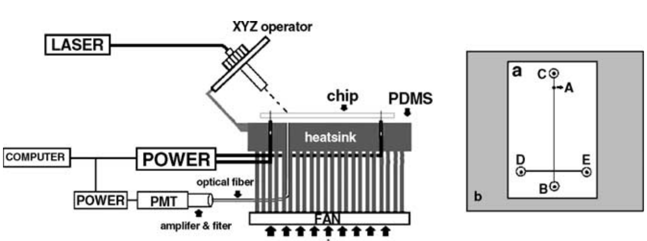

Fig. 1. Schematic of the heat sink-based PDMS microchip system integrated with LIF detection (left) and structure of the PDMS/PDMS microchip (right). A represents the laser focus and detected point on the microchannel. PMT represents the photomultiplier tube. Reservoirs are (B) buffer reservoir, (C) waste reservoir, (D) analytes reservoir, (E) analytes waste reservoir. (a) PDMS microchannel layer, (b) PDMS substrate.

2.1.2. Microchip system

A straight separation PDMS microchannel with cross-sampling channels was made, based on a master composed of a positive relief structure of GaAs for the channels microfabricated in no. 55 Electronic Institute (Nanjing, China) by using standard microphotolithographic technology. The sampling channel of 30 μm width and 18 μm depth and the separation channel of 50 μm width and 18 μm depth were used for the laser-induced fluorescence (LIF) detection. The total length of the separation channel was 3.3 cm.

A Plexiglass-based PDMS/PDMS microchannel was constructed as a usual PDMS/PDMS microchip system on a Plexiglass plate. The influence of Joule heat for this system was compared with the heat sink-based PDMS/PDMS microchip, and the length of the separation channels in two microchip systems was all fixed at 2.0 cm.

2.1.3. Integrated LIF detector

As shown in Fig. 1, on the basis of this heat sink, a laboratory-made LIF detector was constructed for microchip electrophoresis [16]. A laboratory-made power supply provided a stable and continuously variable voltage ranging from 0 to 5000 V. An air-cooled argon ion laser (Sanle Optical Company, Nanjing, China) with a 488 nm excited wavelength was adjusted to be focused on the microchannel with an incident angle of 45° with the X-Y-Z operator under a stereoscopic microscope (XTB-1; Jiangnan Optical Instrument Factory, Nanjing, China). The fluorescence emission signal was collected by an optical fiber of 2 mm diameter connected with an inverted microscope via a 40× objective, and then passing through a 520 nm band-pass filter amplified by a photomultiplier tube (PMT) (Hamamatsu) equipped with an amplifier. A laboratory-made signal-recording system was used to control the power supply and the PMT. Meanwhile, it was used to record the amplified output signals from the PMT.

2.2. Electrophoretic procedure

With our laboratory-made program, the curve of the separation current versus running time was recorded. In all cases, degassed buffer was introduced into the reservoirs and flushed through the channel via vacuum. A 50 mM SDS + 10 mM boric acid solution and 100 mM phosphate-buffered saline (PBS) were used as running buffers. In the beginning, the microchannels were treated with the running buffers for 15 min. All experiments were carried out under the same room temperature of 20 °C.

3. Results and discussion

When electric field is applied on the microchannel, Joule heat would transfer to the surroundings through the running buffer and microchip so that the solution temperature would be determined by not only microchannel structure but also the thermal conductivity of microchip material and surroundings. Table 1 listed the thermal conductivity of the materials that are parts of the microchip system or related to heat dissipation of microchip system. Although it has been reported that inherently larger surface-to-volume ratio of microchannel could allow much more heat to be removed effectively, much lower thermal conductivity of PDMS makes the dissipation of Joule heat difficult again. The upper part of the PDMS microchip could not allow the removal of Joule heat [11]. Therefore, the microchip substrate should be responsible for the quick dissipation of Joule heat. In present system, with the help of very high thermal conductivity and excellent industrial design of the heat sink, the heat sink-based PDMS/PDMS microchip allows fast dissipation of Joule heat in electrophoretic separation system.

3.1. 100 mM PBS as running buffer

To perform the investigation of heat-dissipation efficiency of heat sink-based PDMS/PDMS microchips, 100 mM PBS was used as running buffer at first. Fig. 2 shows the stability of current versus time in normal PMDS/PDMS microchip system compared with in heat sink-based PDMS/PDMS microchip system. As expected, when the applied electric field strength is under 300 V/cm (not shown), no obvious current difference between the heat sink-based and normal PDMS/PDMS microchannels. It means that heat balance can still reach when the applied electric field strength for the PDMS/PDMS microchip is not very high even though the thermal conductivity of PDMS is very low.

But when the applied electric field strength is increased over 300 V/cm, different phenomena were observed in two different systems. Because Joule heat cannot be dissipated effectively to the surroundings, the temperature of running buffer would be increased. It is well known that electric conductivity of solution would increase if its temperature increased. So, these two procedures would cycle until the heat balance could reach. Therefore, it can be observed from Fig. 2 that with normal PDMS/PDMS microchannel, the current would continuously increase without stop even within running time of only 25–30 s. The higher the electric field strength on the microchannel was, the faster the separation current increased. It is observed that this increase could not stop until bubbles were generated in microchannel. Such results clearly demonstrated that heat balance is not easy in normal PDMS/PDMS microchip electrophoresis, and electric field strength more than 300 V/cm could not be applied on normal PDMS/PDMS microchip.

While, it can be observed from Fig. 2 that with the heat sink-based PDMS/PDMS microchip, Joule heat of the system can be easily and effectively dissipated. Compared with normal PDMS/PDMS microchip system, the curve of the separation current became flat very quickly. Heat balance reached in relatively short time and even under the high electric field of 550 V/cm. Therefore, it has been demonstrated that with the help of heat sink, Joule heat of PDMS/PDMS microchip electrophoresis could be effectively dissipated even under electric field strength more than 300 V/cm.

Table 1
Thermal conductivity of the materials that are parts of the microchip system or related to heat dissipation of microchip system

Materials	Thermal conductivity ($W m^{-1} K^{-1}$)	References
Air	0.0264	[8]
SiO_2 or glass	1.46	[8]
PDMS	0.2	[11]
Water	0.59	[1]
Aluminum	222	[17]
Copper alloy	377	[17]

3.2. SDS as running buffer

One of our main objectives is to perform micellar electrokinetic chromatography (MEKC) on the PDMS/PDMS microchips in the near future. Because of the high concentration of SDS, much more Joule heat was generated so that MEKC would be very difficult to be carried out with normal PDMS/PDMS microchannels. In the experiments, 50 mM SDS and 10 mM boric acid buffer was used as background electrolytes. The comparison between normal PDMS/PDMS microchip and heat sink-based PDMS/PDMS system was presented in Fig. 3. For normal one, the turning point of Ohm's curve is located at 550 V/cm. While with the heat sink-

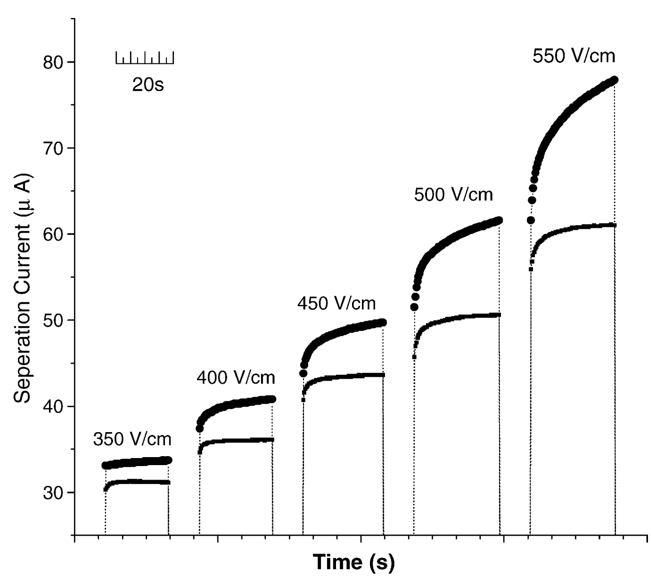

Fig. 2. The stability of current with time in normal PMDS/PDMS microchip system (upper) compared with heat sink-based PDMS/PDMS microchip system (lower) using 100 mM PBS as running buffer. The results were measured within 25–30 s in different electric fields, respectively.

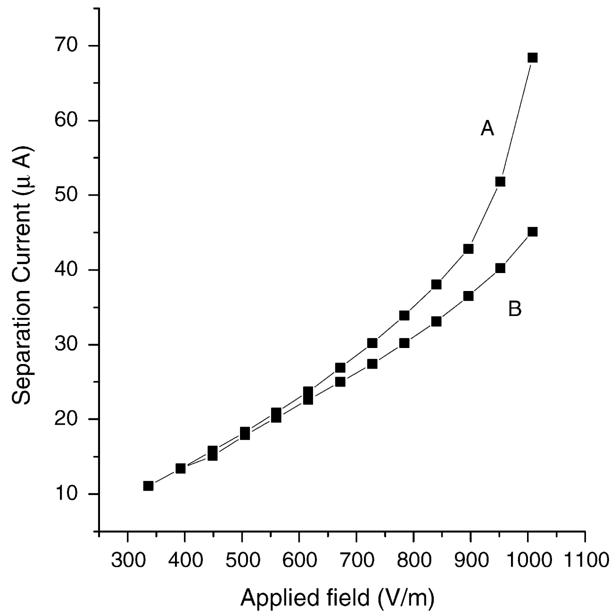

Fig. 3. Comparison of Ohm's law plots between normal PMDS/PDMS chip (A) and heat sink-based PDMS/PDMS chip (B) in 50 mM SDS + 10 mM boric acid buffer.

based system, the turning point increased to be 800 V/cm. This significant difference demonstrated that the effective range of separation electric field strength in PDMS/PDMS system is greatly enlarged after the introduction of heat sink.

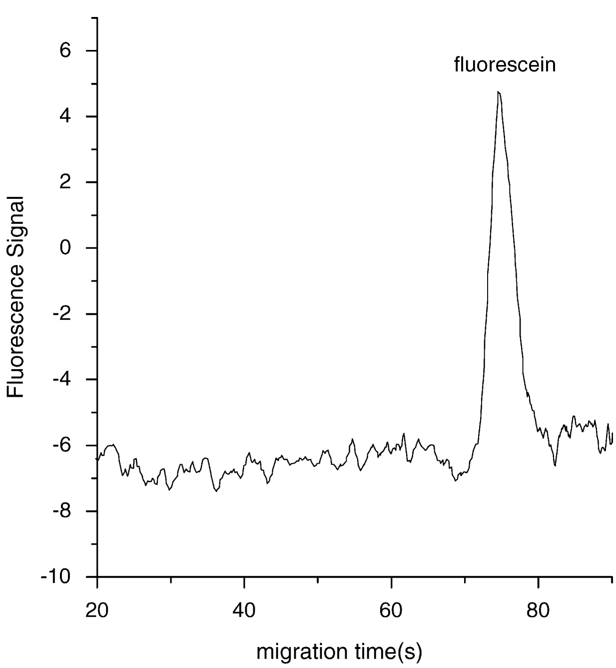

Fig. 4. Electropherogram of fluorescein with 100 mM PBS and 1 mM SDS as running buffer. Parameters: length of separation microchannel: 2.5 cm; separation electric field strength: 280 V/cm; sample voltage: 300 V; sample time: 1 s; multiple voltage for PMT: 850 V.

3.3. Electrophoresis of fluorescein with LIF detection

A LIF detection system was integrated in our system on the base of heat sink. With this integrated system, the accurate alignment of optical routes can be operated with the help of the microscope. This promised successful detection of fluorescein as the sample with our integrated system. As shown in Fig. 4, with 100 mM PBS + 1 mM SDS as running buffer, electrophoresis of fluorescein with the concentration of 1.0×10^{-6} M was performed successfully. The detection limit for fluorescein was estimated to be 4×10^{-8} M (S/N = 2). The theoretical plate number of 2750 (for 2.5 cm separation channel, corresponding to 110,000/m) was obtained for this electrophoretic process. Further studies on the separation and detection of biological and other materials with this new integrated system were undergoing. Such high separation efficiency with high concentration running buffer demonstrated that there would be more applicative for microchip electrophoresis of PDMS.

4. Conclusions

Although the larger ratio of surface to volume of microchannel allows quick dissipation of Joule heat in microchip electrophoresis, very low thermal conductivity of polymers makes this dissipation much difficult. Experimental results with present new heat sink-based PDMS microchip system demonstrated that dissipation of Joule heat in PDMS microchip electrophoresis could be greatly improved. Furthermore, with the integrated laser-induced fluorescence detector, successful electrophoresis of fluorescein using high concentration buffers confirmed the validation of total system. It is believed that further study with present PDMS/PDMS microchip system would help extensive application of PDMS-based systems in more fields such as MEKC study.

Acknowledgement

The authors are greatly thankful for the financial support of the National Natural Science Foundation of China (NSFC, nos. 20299030, 90206037, 20205007, 20305009).

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