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Chromatomembrane method for the continuous separation of substances

L.N. Moskvin

Department of Chemistry, St. Petersburg State University, 2 Universitetsky Prospect, Stary Petergof, St. Petersburg 198904, Russian Federation

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Abstract

A novel chromatomembrane method for the continuous separation of substances was developed. Mass exchange in liquid–liquid and liquid–gas systems proceeds according to chromatographic principles. Capillary effects in porous hydrophobic membranes with two preferential pore types are utilized to realize independent transport of phases in arbitrary directions. The macropores form channels for the polar liquid phase. The non-polar liquid or gas phase passes through the micropores, which are inaccessible to the polar phase because of capillary pressure. The possibilities of the method are demonstrated by schemes of continuous separation with preset extraction coefficients, schemes of application of the method in flow-injection analysis and results obtained in chromatomembrane blood oxygenation.

1. Introduction

As early as 1949, the founder of liquid and gas–liquid chromatography, Martin [1], formulated the thought that chromatography would become a technological method only when it became possible to make the chromatographic separation process continuous. He also proposed a scheme for the principle of a continuous two-dimensional chromatographic process. Continuous chromatographic separation of substances becomes possible when two phases move independently at right-angles to each other. In the 1950s–1970s, numerous attempts were made to realize this idea [2–16]. In all these studies, as a basis the principle of mechanical shift of the sorbent layer or the liquid phase support in relation to stationary inlet systems for analytes and eluents and stationary effluent collectors was assumed. Experimental evidence for the conceptual possibility of continuous chromatographic separation within the proposed scheme was a general result of these investigations. This direction did not result in practical development, mainly owing to technical difficulties of realizing a separation scheme with mechanical transfer of one of phases.

Since the 1970s, the search for continuous separation methods shifted more and more into the field of membrane processes. Considerable progress was made in electrodialysis and reverse-osmosis water determination and in gas-diffusion separations. The method of membrane distillation opened up greater opportunities. However, membrane methods are usually found to be effective for enrichment or impoverishment of the final product with respect to certain components. Progress with the selective membrane

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isolation of substances from complex many-component mixtures has been more modest. The greatest hopes here were connected with liquid extraction membranes. Fundamental work in this direction was accomplished in the late 1960s–early 1970s [17–22]. The main result was experimental evidence for the conceptual possibility of realizing membrane extraction processes in the dialysis and electrodialysis regimes. The greatest success in the practical application of the method was achieved using membranes in the form of hollow fibres and with a membrane extraction in the stabilized emulsion. The conceptual possibilities of membrane extraction are virtually exhausted [23] and in the future one can expect only technical improvements in the construction of membrane units and concrete methodical or technological work oriented at the extraction of specific substances [24].

It became increasingly obvious that non-traditional solutions are needed for real progress in the methodology of the continuous separation of substances. This paper gives an account of the principles of a chromatomembrane method for continuous separation in two-phase liquid–liquid and liquid–gas systems [25]. Investigations of the retention mechanism of the stationary gas phase in the liquid–gas chromatography (*i.e.*, chromatography with a stationary gas phase) [26] preceded the idea of the chromatomembrane method. It was noted that even with virtually totally degassed aqueous phases the volume of the stationary gas phase retained in the pores of microporous hydrophobic supports can reach up to 50% of the total free volume of the column [27]. This effect has a natural explanation. In the pores of a support that is non-wettable by water, capillary pressure arises which prevents them from filling. Whilst the pressure of a liquid does not exceed the sum of the capillary pressure and the pressure of gas in the pore space, the liquid cannot fill the pores. With sufficiently small pore radii the ultimate case can be realized when the capillary pressure exceeds the liquid-phase pressure. Then, even in the absence of a gas in the system, the pore space is inaccessible to a liquid that does not wet the support and the pores are found to be filled only with its vapour. Hence the retention of non-polar liquids in the pores of inert hydrophobic supports in reversed-phase liquid chromatography is also explained.

2. Results and discussion

The idea of the chromatomembrane process originated from the foregoing discussion. The mass exchange process is carried out in the capillary–porous media of hydrophobic material with two preferential pore types differing in size, which is bounded on two sides by microporous hydrophobic membranes (Fig. 1). Macropores form channels for passage of the polar liquid phase and micropores form channels for the passage of the non-polar liquid phase or the gas. The absence of mutual phase mixing is guaranteed by the difference in pressures under which polar (P_1) and non-polar (P_3) phases are supplied into the system. The pressure within all the volume occupied by the non-polar phase is maintained lower than the polar phase pressure. Hence the polar phase pressure at the outlet from the mass exchange chamber (P_2) must exceed the pressure at the inlet of the non-polar liquid or gas in it (P_3), *i.e.*,

$$P_3 < P_2 \quad (1)$$

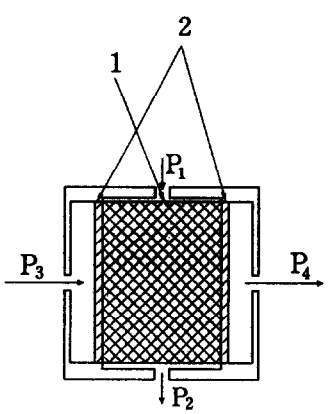

Fig. 1. Scheme of chromatomembrane mass-exchange process. 1 = Hydrophobic medium with two preferential pores types; 2 = microporous membranes; P_1, P_2 = polar phase pressures; P_3, P_4 = gas or non-polar phase pressures at the inlet and outlet of the mass-exchange chamber, respectively.

As a result, the non-polar liquid phase or gas cannot penetrate from the micropores to the macropores. In turn, the capillary pressure (P_c) prevents its displacement out of the micropores by the polar phase. The value of P_c depends on the surface tension (σ), the contact angle of porous material (θ) and the pore radius (r):

$$P_c = \frac{2\sigma \cos\theta}{r} \quad (2)$$

For liquids that do not wet the pore walls the P_c value is negative and is the greater the smaller is the pores radius. As long as the condition

$$P_1 < P_4 + P_c \quad (3)$$

is valid, micropores remain inaccessible to the polar phase. When the limiting conditions $P_2 > P_3$ and $P_1 < P_4 + P_c$ are fitted, the possibility of transferring two phases independently within a mass exchange space formed by the hydrophobic biporous medium arises. In principle, a layer of any granulated hydrophobic porous sorbent can be considered as a medium for the realization of the chromatomembrane process. In this case pores within granules form channels for passage of the non-polar liquid or gas phase. Channels for the polar liquid phase are formed in the space between the granules. However, such a scheme of biporous medium formation has the serious disadvantage that connections between the internal pore volumes of separate granules and between granules and bounding membranes take place only at the points of contact. At these points the cross-section for passage of a non-polar liquid flow contracts sharply. Correspondingly, the possibility of regulating the rate of this flow becomes very restricted within the permissible pressure range. Because of this, to realize the chromatomembrane process it is necessary in the general case to have a continuous layer of hydrophobic material with two types of open pores, differing in size.

The scheme presented by Fig. 1 corresponds to the case of flows of the phases moving at right-angles to each other. The mass exchange is achieved in accordance with principles of a chromatographic process with the only difference that convectional supply of both phases to the boundary and withdrawal from it increase the rate of inter-phase exchange. There is inherent in the method a chromatographic mechanism of exchange between phases. On the other hand, separated flows of the two phases into and out of the mass-exchange zone is possible only with the application of membranes (in order to provide an input of non-polar phase flow at a pressure lower than that of the polar phase). Finally, and more important, the method allows the combination of a high mass exchange efficiency inherent in chromatographic processes with a continuously functioning regime of separating units which is characteristic of membrane methods.

Porous polytetrafluoroethylene (PTFE) was used as a membrane material and for filling the mass-exchange chambers throughout. The average radius of the micropores was 0.3 μm and that of the macropores was 200 μm for analytical cells and 2000 μm for blood oxygenators. Further progress in method development will be dependent on the creation of special polymeric materials with the necessary structure. The main requirement is the presence of two types of open pores with a minimum size dispersion within each type. Porous PTFE, although it shows chemical durability, has two essential defects: independently of the fabrication one fails to ensure a high size uniformity of the micropores by size, and second, there is a change in the contact angle on long-term contact with aqueous solutions. These defects are not crucial for the method, but they introduce specific limitations.

The chromatomembrane process allows continuous chromatographic separations to be performed on account of the creation of two intersecting flows of the phases. However, greater opportunities are opened up by the scheme of continuous separation which is inherent only in this method (Fig. 2). When using mass-exchange chambers connected along the line of the extracting agent feed, each of them executes only one specific function. Extraction of components A and B takes place in the first chamber, and in the next two chambers re-extraction of the individual components is carried out. With such a scheme it is possible to regulate within broad limits the coefficient of concentration of the

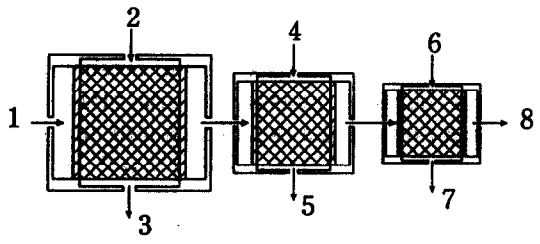

Fig. 2. Scheme of chromatomembrane separation of a many-component mixture. 1 = Extraction agent; 2 = many-component solution; 3 = non-extracted components; 4 = eluent for substance A; 5 = concentrate of A; 6 = eluent for substance B; 7 = concentrate of B; 8 = recycling of extraction agent.

extracted substances on account of the regulation of the volumes of the chambers and of the flow-rate ratio of the exchanging phases.

Possibilities of the chromatomembrane method for the concentration and isolation of individual substances are considered below. The distribution coefficient in the phase system used is an individual criterion for each extracted substance. The rate of shift of the zone of an extracted substance with the flow of an aqueous solution obeys the law common to all chromatographic processes:

$$U_i = \frac{U_0}{1 + K_{D1}(V_1/V_2)} \quad (4)$$

where K_{D1} is the distribution coefficient at the extraction stage, U_i the rate of the shift of the ith component zone with aqueous solution flow, U_0 the rate of supply of the solution and V_1/V_2 the ratio of volumes occupied by the micro- and macropores. Correspondingly, in order to ensure the absence of an extracted substance breakthrough, the rate of supply of the extraction agent must meet the condition

$$h_1/U_i > l_1/U_{ex} \quad (5)$$

where h_1 is the height of the extraction chamber, l_1 its width and U_{ex} the rate of supply of the extraction agent. This condition is valid on assuming the absence of dispersion of the zone front of the extraction agent. As the theoretical evaluation of zone dispersion is difficult, it is necessary in practice to determine experimentally the minimum admissible value of U_{ex}.

The border condition for the re-extraction stage can be written as

$$l_2/(U_i)_{ex} > h_2/U_{el} \quad (6)$$

where l_2 and h_2 are width and height of the re-extraction chamber, respectively, $(U_i)_{ex}$ the rate of shift of the front of the separating substance zone with extraction agent flow and U_{el} the eluent flow-rate. Taking into account the phase inversion in relation to the extraction process, we have

$$(U_i)_{ex} = \frac{U_{ex}}{1 + 1/K_{D2}(V_1/V_2)} = \frac{U_{ex}K_{D2}V_1}{K_{D2}V_1 + V_2} \quad (7)$$

where K_{D2} is the distribution coefficient at the re-extraction stage. Taking into account that conditions were chosen when $K_{D2} \rightarrow 0$ for the re-extraction stage, one can carry out the elution with a minimum rate. Correspondingly, the ultimate values of the concentration coefficients may be obtained, which are determined by the solubility of the extracted substance in the eluent and by the extraction isotherm pattern.

As examples of analytical applications of the method, some flow-injection analysis methods with chromatomembrane isolation of detected components from liquid and gas phases are considered. The distinctions between liquid and gas analyses with chromatomembrane preconcentration became apparent in the connection scheme of the mass-exchange chambers (Fig. 3). In gas analysis the sample is passed through the chromatomembrane cell from the side of the

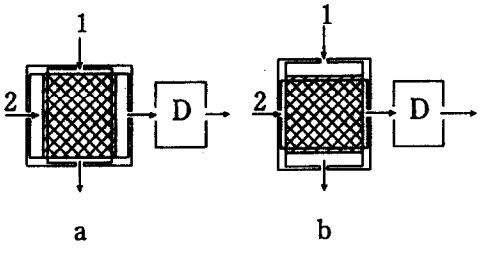

Fig. 3. Scheme of flow-injection analysis with chromatomembrane preconcentration of analyte substances. (a) Analysis of aqueous solutions; (b) analysis of gases. 1 = Analyte solution (a) or gas (b); 2 = extraction agent (a) or aqueous solution absorbing analysed gaseous compounds (b); D = flow-through detector.

limiting hydrophobic membranes. The absorbing aqueous solution after the cell is directed to the potentiometric or photometric detector. In liquid extraction, a photometric detector is connected to the extraction agent outlet from the chromatomembrane cell. The reagent is directed to the cell from the second hydrophobic membrane side and the analyte solution from the side of the free inlet to the mass-exchange chamber.

Two schemes of analysis are possible in both instances: continuous and discrete. With a continuous regime of the analyte solution or gas supply, strict regulation of the pressures of both phases in the cell is necessary. With the discrete regime a consequent phase passage through the chromatomembrane cell is realized by switching the inlet and outlet channels for the phase to be the stationary phase at a given moment. The discrete regime is to be preferred for a common scheme of flow-injection analysis.

Fig. 4 presents an experimental device for the determination of SO_2 in the air. The absorbing aqueous solution is drawn into the plunger sampler (2) through a valve (3). The macropore volume of the chromatomembrane cell (4) is filled by the absorbing solution, valves 3 and 5 being open and valves 6 and 7 on gas lines closed. The air sample is drawn into the plunger sampler (9) through the port (8) and is then passed through the cell (4), the valves 6 and 7 being open and valves 3 and 5 closed. After passage of the gas sample the valve pairs 3–5 and 6–7 are switched to the former position and the solution with absorbed SO_2 is displaced by the initial solution from the macropores of the cell into the flow-through photometric detector (10). Flow-rates of the gas and aqueous solution are selected from preliminary experiments. In the discrete regime of analysis, there is no need to regulate the aqueous solution and air feed pressures in relation to each other to ensure fulfillment of the conditions in Eqs. 1 and 2 for realization of the chromatomembrane process. In this instance the limiting pressure is the same for both phases and must not exceed the capillary pressure inherent in the material of the membranes bounding the cell and the radius of the pores within them. The calculation of capillary pressure is difficult because of the wide distribution of pore radii in the membranes. Hence we determine the pressure of aqueous solution percolation through the membrane. Correspondingly, the rates of passage of both phases are selected within the pressure range at the inlet of the cell, which lies below the established percolation value.

Fig. 5 shows the output signal pattern for photometric detection of sulphur dioxide absorbed by a solution of iron (III)–phenanthroline complex. The value of the signal amplitude varies proportionally to the absorption time. Correspondingly, the detection limit can be

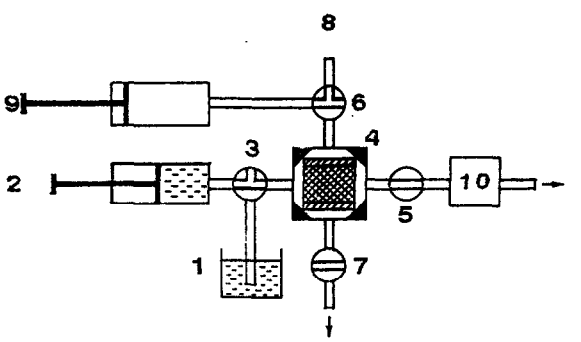

Fig. 4. Scheme of experimental device for determination of SO_2 in air. 1 = Vessel containing absorbing solution; 2, 9 = plunger samplers; 3, 5, 6, 7 = valves; 4 = chromatomembrane cell; 8 = port; 10 = flow-through photometric detector.

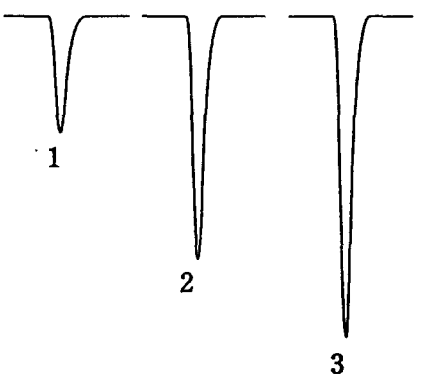

Fig. 5. Output signal pattern for photometric detection of SO_2 absorbed from air by a solution of iron(III)–phenanthrene complexes. Time of absorption in chromatomembrane cell: (1) 0.5; (2) 1.0; (3) 1.5 min. SO_2 concentration in air = 0.5 $\mu g/dm^3$.

altered within a broad interval. Analogous dependences were obtained for the determination of copper in water using extraction of its dithizone complex and for the determination of hydrogen fluoride in air with potentiometric detection.

Chromatomembrane blood oxygenation may serve as an illustration of the technological application of the method. The chromatomembrane method offers a conceptually new scheme of blood oxygenation which approaches as closely as possible the natural gas exchange in the lungs, concerning first of all the high total mass exchange rate. In this instance the flows of blood and air are directed into the chromatomembrane cell simultaneously. In order to provide an excess blood pressure *vs.* air throughout the volume of the cell, the blood is collected in a vessel mounted at a height of 1 m. Correspondingly the air pressure at the inlet to the cell is kept lower than 10 kPa. The data obtained for oxygenation of donors' blood (Table 1) illustrate the efficiency of the chromatomembrane process. Advantages of membrane oxygenation include the minimum priming volume, the opportunity to utilize atmospheric air and arbitrary variation of the size of the mass-exchange space, which allows comprehensive oxygenation, from auxiliary to extracorporal.

The necessary partial pressure of oxygen in the blood is reached with commensurable volume rates of air and blood and with a twentyfold lower oxygen rate. During closed-circuit circulation the oxygenator does not exert a traumatizing influence on formal elements of blood after prolonged operation.

The possible fields of practical application of the chromatomembrane method are not restricted to the presented illustrations. The method is applicable theoretically to all mass-exchange processes in liquid–gas and liquid–liquid systems. At present, for instance, we are elaborating a scheme for water deoxygenation, with the conceptual possibility of utilizing chromatomembrane units for membrane distillation.

3. References

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Table 1
Changes in donor blood gas composition during oxygenation with different ratios of volume rates of gas and blood flows at the oxygenator outlet

Parameter	Before oxygenation	Volume flow ratio			
		1:2	1.5:1	1:20	1:5
Air oxygenation					
$p(O_2)$ (mmHg)	32	97	115		
$p(CO_2)$ (mmHg)	136	38	33		
pH	6.63	6.81	6.92		
Oxygen oxygenation					
$p(O_2)$ (mmHg)	29	215		100	160
$p(CO_2)$ (mmHg)	150	32		41	36
pH	6.68	6.81		6.71	6.75

1 mmHg = 133.322 Pa.

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