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Surface-area expansion with monolithic open tubular columns

Radim Knob [a,b], Chadin Kulsing [c], Reinhard I. Boysen [c], Mirek Macka [a,*], Milton T.W. Hearn [c]

[a] Australian Centre for Research on Separation Science (ACROSS) and School of Physical Sciences, University of Tasmania, Private Bag 75, Hobart TAS 7001, Australia
[b] Department of Analytical Chemistry, Faculty of Science, Palacky University in Olomouc, 17, Listopadu 12, Olomouc 77146, Czech Republic
[c] Centre for Green Chemistry, School of Chemistry, Monash University, Melbourne, Victoria 3800, Australia

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ABSTRACT

This review covers various approaches now available to enhance the surface area of stationary phases fabricated in the porous layer open tubular (PLOT) format for use in liquid-phase-based separation techniques and catalytic applications. We focus attention on the preparation of porous polymers (monoliths), since many procedures have already been described related to the production of PLOT columns with distinctive properties and coatings at the column wall. We discuss advantages and limitations of these methodologies with regard to materials used and the demonstrated application.

Contents

1. Introduction

Recent growth in the life sciences has brought increased demand for the fabrication of new stationary phases required for use in high-resolution separation techniques and widely exploited in research. Increased separation performance and binding capacities are highly desirable in diverse application fields (e.g., proteomics, metabolomics, environmental analysis and medicine). Due to recent trends in miniaturization [1,2], fast, effective approaches are needed in order to solve advanced analytical tasks by separation techniques based on chromatographic and electrophoretic principles.

Fused-silica capillaries play an essential role in separation science. Used in the open-tubular format, in packed beds with particles, or filled with a monolith, they are mainly employed in capillary gas

* Corresponding author. Tel.: +61 3 62266670; Fax: +61 3 62262858.
E-mail address: mirek.macka@gmail.com (M. Macka).

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chromatography (GC) and liquid chromatography (LC), capillary electrophoresis (CE) and capillary electrochromatography (CEC).

In CEC, where the overall migration behavior is the result of interplay between chromatographic retention and electrophoretic migration, the stationary phase is responsible for generating the electroosmotic flow (EOF). Flat plug-like flow profiles in CEC offer higher efficiencies compared to parabolic flow in pressure-driven techniques. The open tubular column (OTC) format has found wide application, due to the advantages associated with the relative ease of flushing the capillary, the lower pressure drop with pressure-driven flow, and the availability of on-column (on-capillary) optical detection [3,4]. However, the properties of fused-silica capillaries bring well-known difficulties with regard to the reproducibility of the surface, its changes with time or when exposed to interactive chemical environments. In order to deal with these challenges of the fused-silica surface, a wide variety of approaches have been invented to modify the silica surface.

Numerous forms of stationary-phase materials can be introduced, dynamically or covalently attached onto the capillary wall [e.g., small molecules, such as amines, brush-type ligands, proteins, polymers as monolayers or successive layers, or nanoparticles (NPs)], as recently reviewed [5]. Such modification helps to shield the capillary surface from undesired interactions, especially in protein and peptide analysis, or to control the EOF, which is essential for rapid, efficient and reproducible CE separation. However, thin coating layers (in the nanometer range) often result in poor capacity, which hampers applicability when a large surface area is required. Low loadability and lack of suitable on-capillary detectors in the past were the primary reasons for OTCs not being widely used in LC [6].

Porous layer open tubular (PLOT) columns were introduced to overcome the above limitations in capacity. The inner surface is coated with a stationary phase that has porous microstructure, which greatly increases the effective surface area, and thus greatly increases the capacity. PLOT columns were first introduced to GC by Golay [7], and this format has become very popular for its significant improvements in efficiency and speed of analysis over packed-bed capillaries. PLOT columns are widely produced by several manufacturers with numerous established applications [8].

Porous layer structures can provide improved capacity due to their surface area being larger than that of non-porous wall-coated polymeric coatings. Although the solid to liquid ratio for PLOT columns is lower than that of packed or across-the-lumen monolithic columns of the same inner diameter, their capacities are still much greater than that of unmodified or packed-bed capillaries and suffice for most applications. With capillaries of narrow capillary diameters (e.g., ≤ 25 μm), acceptably high efficiencies can be achieved [9]. As principal advantages, they offer significantly higher permeability, the possibility of rapid column flushing and regeneration, and less demanding requirements on pump pressures. Similar to monolith systems, but different to packed columns, there is no need to use frits.

Approaches leading to PLOT and more specifically monolithic PLOT columns with increased surface area for liquid-phase-based separation techniques, as well as for catalytic applications, were the subject of extensive research in recent years. This level of interest is also reflected in several reviews with applications of OTCs focused on GC [10], open tubular LC [11,12], and CEC [13], and applications of these techniques were recently reviewed by Cheong [5].

In this review, we focus on new materials and approaches leading to formation of monolithic PLOT stationary phases. Specifically, this review addresses how to create a monolithic porous layer on the capillary wall, and the associated different ways that the layer thickness and other parameters can be governed. Many materials can be employed to achieve the formation of such stationary phases, such as silica, porous polymers or immobilized NPs providing different structures, distinctive porosities and pore sizes, and a wide variety of surface functionalizations and chemistries.

2. Fabrication of PLOTs

Using different technologies and materials, significant progress in the fabrication of PLOT columns was made in recent years. A critical aspect underpinning these achievements lies in the manner of attaching the stationary phase to the capillary wall and the prevention of blockage or narrowing of the capillary lumen. Different procedures can be employed to control these processes, which play crucial roles in forming reproducible PLOT capillaries. To date, no general procedure reported can be utilized to accommodate the large variety of synthetic monomer/polymer combinations due to the diversity of their chemical characteristics.

When a thicker coating is desired, capillary clogging is more likely to occur during fabrication and usage, so selection of operating conditions has to be careful. As shown by Kulsing et al. [14] and Al-Hussin et al. [15], stationary phases of considerable thickness are most desirable, since these show a significant increase in the surface area compared to the bare open-tubular capillary, whilst keeping the advantages of good flow-through properties.

The surface properties of the capillary surface are the governing factor in forming suitable immobilized stationary phases, since strong bonding to the wall is required; otherwise, bleeding of the coating will occur. Recent challenges in preparing PLOT stationary phases with narrow diameter capillaries (e.g., ≤25 μm) showed that different behavior can occur depending on the properties of the wall, which play important roles in the fabrication processes, affecting the properties of the stationary phase in terms of thickness and porosity.

Beside formation of polymeric or particle stationary phases, another way to increase the surface area is by etching, as studied by Pesek et al. [16]. In this way, large (e.g. 1000-fold) increases in the surface area of the capillary wall have been reported.

More recently, silica etching by supercritical water was introduced by Karásek et al. [17]. Such procedures allow precise tuning of the surface microstructure by varying the etching conditions together with the interesting possibility of controlling the internal diameter of a capillary along its entire length.

2.1. Sol-gel method

Silica is the traditional separation medium for chromatographic methods with a major role in most of the micro-particulate packing materials and silica monoliths [18]. Such materials possess advantages of high mechanical stability, user-defined pore size and tunable permeability related to porous structures. However, chemical stability is an issue when operating at extreme values of pH.

Porous OTCs were first reported about two decades ago, Tock et al. [6] exploited a sol-gel process for preparing a thin layer of porous silica. The procedure consisted of a solution based on tetraethoxysilane (TEOS) or another alkyloxysilane that formed an aqueous sol solution followed by gelation with an acidic or alkaline catalyst, resulting in a continuous network. Polycondensation and linking of additional silanol groups takes place, with conditions, such as pH, temperature or reagent concentrations, controlling the properties of the resulting material. Formation of PLOT stationary phases requires optimized conditions for the pre-gelation step, mostly in terms of time and temperature. However, these modifications have been shown to lead to poor capacity and retention of polyaromatic hydrocarbons [19].

Later, Crego et al. [20] improved the procedure to obtain a thicker coating inside small-diameter capillaries by introducing ethanol into the reaction mixture to enhance TEOS solubility. C_{18}-modified 5-μm