Chemical Engineering Science 124 (2015) 179–187

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Review

Metal-organic frameworks as stationary phases for chiral chromatographic and membrane separations

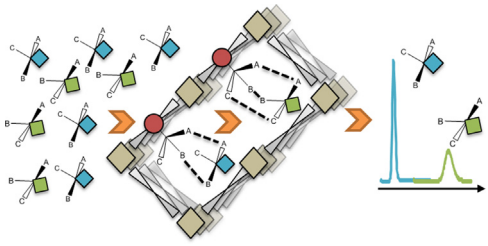
T. Duerinck, J.F.M. Denayer *

Department of Chemical Engineering, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussel, Belgium

HIGHLIGHTS

- Introduction of chirality in MOFs by direct synthesis (linker, cluster) or postsynthetic modification.
- Chiral MOFs as GC, LC stationary phases and membranes.
- Separation of small organics (alcohols, acids), sulfoxides and amino acids by Chiral MOFs.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 July 2014
Received in revised form
5 October 2014
Accepted 9 October 2014
Available online 30 October 2014

Keywords:
Chiral
Metal-organic frameworks (MOF)
Chromatography
Enantiomers
Adsorption
Separation technology

ABSTRACT

Nowadays thousands of stable MOF structures are known and investigated for guest-host adsorption in liquid and gas phase. Here, in this review, we focus on the current state-of-art regarding chiral resolution using homochiral MOF structures. Synthesis routes and pore architectures are critically reviewed along with the reported chiral resolution potential for small chiral organics. Besides gas and liquid phase adsorption of racemates, special attention is given to the application of these materials as stationary phases (GC, HPLC) and their use in membrane applications.

Current state-of-art clearly illustrates the promise that MOFs hold for chromatographic separations: versatile routes to modification of achiral MOF structures or synthesis of intrinsic chiral pore architecture, tunable pore size and structure, and formulation in beads for packed bed technology or substrate growing for membrane technology. However, it is also clear that, in spite of several initial reports, much work still needs to be done as questions that is, regarding mechanical, thermal, and long term stability of MOF chiral stationary phases, shaping of such MOFs into monodisperse spheres needed to achieve high resolution, compatibility with mobile phases etcetera remain unanswered.

1. Introduction

In view of the large number of reported structures, rather limited attention was devoted to the design, synthesis and application of chiral metal-organic frameworks (MOFs). (Qiu and Zhu, 2009). MOFs have been hinted as promising materials for various applications such as (optical) sensor, catalysis, gas purification and promising stationary phases in GC and LC. (Qiu and Zhu, 2009; Wenbin, 2007) The use of MOFs as a chiral stationary phase or membranes is topic of this review. These materials may provide a stable, reliable and cost efficient alternative stationary phase to conventional HPLC or GC columns due to large flexibility in design. Similarly, MOFs can be used to fabricate membranes or be embedded in existing membranes to enhance their intrinsic properties. Versatility of this type of porous materials could very well be the key towards well-characterized chiral stationary

* Corresponding author. Tel.: 32 26 2917 98; Fax: +32 26 2932 48
E-mail address: Joeri.Denayer@vub.ac.be (J.F.M. Denayer).

http://dx.doi.org/10.1016/j.ces.2014.10.012
0009-2509/

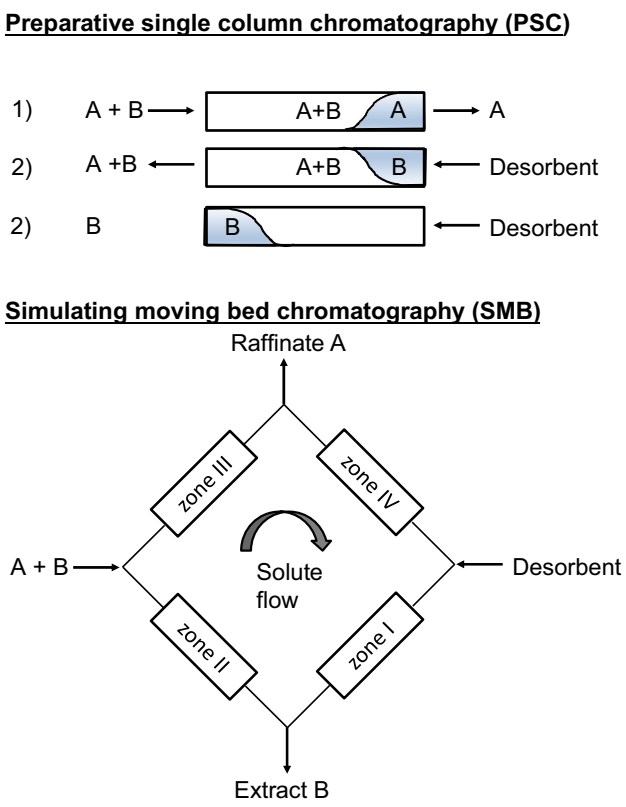


Fig. 1. Schematic representation of PSC and SMB technology - Mixtures of components (here A and B) are loaded on a column with a stationary, selective phase. After an adsorption stage (step 1 or zone III) where the raffinate A is collected, Extract B can recovered during a limited time frame (step 2 or zone I) during the regeneration step of the column. The key difference is that while PSC is discontinues and relies on a single column, SMB used at least four or more column with identical packing that are being switched to allow for continuous operation.

phases for liquid chromatography (LC) and gas chromatography (GC) for analytical or even preparative purposes. Both the organic linker and connecting metal cluster can be varied and optimized to create a match in size and affinity between the stationary phase and the target molecule.

The separation of chiral components in its pure enantiomers is of great importance to industry, mainly pharmaceutical companies. More often than not, a single pure isomer is the active component of drugs and the other isomer may have dramatic, negative side effects. (Smith, 2009) Preparative single column (PSC - (Cavazzini et al., 2011)) or simulating moving bed chromatographic separation (SMB - (Rajendran et al., 2009)) is expensive but often unavoidable as a chiral selector is needed to purify such chiral mixtures. Fig. 1 illustrates some of the key differences between PSC and SMB technology.

The underlying mechanism for this chiral resolution can be simplified to the three point interaction theory (Fig. 2) where it is assumed that an attractive interaction between a guest and host occurs. In this case, the functional groups of a mobile agent (guest) and a chiral site in the porous material [host] may interact partly or completely as shown in Fig. 2. On the left, a partial match between guest and host is shown whereas a full 3-point interaction is depicted on the right. In a binary component resolution, the latter interaction (right side) would result in a longer retention time or preferential inclusion over a partial (1 or 2-point) interaction. Although the model has been criticized and adapted over the decades, the basic principle still holds.(Lämmerhofer, 2010) In fact, it is the underlying thermodynamic interaction that will determine a more or less favourable interaction, thus even one or two favourable interactions may lead to a retention of one component. It is the difference in Gibbs free energy that will determine the separation potential in chromatographic applications.

Each of the available selectors in the stationary phase forms a complex through specific interaction with a preferential enantiomer, there retaining it longer in the column. Another method is derivatization of the enantiomer with another, pure enantiomer. This will give yield to a diastereomer mixture that can be separated on an achiral column. A third option is the use of a chiral auxiliary component. This component is added to the mobile phase and forms a labile complex with the target eluent, allowing for chiral resolution. The drawback of this method us that recuperation of the auxiliary component is not an option and that it may interfere with detection of target components.(Lämmerhofer, 2010)

Commercially available chiral stationary phases (CSP) for gas chromatography GC) can be divided in roughly three categories on the basis of their underlying interaction mechanism. Chiral resolution through preferential hydrogen-binding interactions is typically achieved using post synthetic modification of amino functionalities, present in a parent stationary phase. Other CSPs are based on enantiomer complex formation through interaction with a chiral metal complex in the stationary phase structure or enantiomer inclusion. The latter is the underlying mechanism for cyclodextrin derivative columns. Much as for GC, CSPs can be categorized for HPLC on the basis of its chiral selectors towards molecular size. (Cavazzini et al., 2011; Lämmerhofer, 2010). Marcomolecular selectors are typically biopolymers derived from proteins or polysaccharides with intrinsic chirality, and synthetic polymers with a nitrogen derived functionality (polytartaramides, poly(meth)acrylamides). Macrocyclic selectors are based in the principle of inclusion. These CSPs are based on cyclodextrines, macrocyclic antibiotics and chiral crown ethers. Low-molecular mass selectors rely much more on specific interactions and can be categorized as such: donor-acceptors (Pirkle-tpye), chiral ion-exchange and ligand exchange selectors (chelating agents).

Here, in this article the application of metal-organic frameworks as stationary phases on chromatography is critically reviewed. Metal-organic frameworks hold great promise as the accessible surface and pore volume is often much higher than for silica, zeolite or carbon materials. These materials are synthesized by coordinatively linking metal ions or small metal(oxo)clusters to bi- or multidentate organic molecules.(Yaghi et al., 1998) In this way a well-defined three-dimensional crystal structure, with virtually no inaccessible pockets, can obtained. The great strength of this class of materials comes from the nearly limitless number of metal and organic linker combinations. By playing with one or both of the building blocks, one can in theory design a specific material for a specific target application.(Falkowski et al., 2012; Ma and Lin, 2010; Nickerl et al., 2011) Examples of rational design leading to new, theoretical structures have been reported for CO_2 adsorption (Farha et al., 2012; Wilmer et al., 2012) and Xe/Kr separation (Sikora et al., 2012) It is the match between the size and shape of the molecule and pore architecture that will define its separation potential. The importance of confinement effects was confirmed by molecular simulations.(Bao et al., 2009, 2012)

The great challenge lies with the issue of controlling the pore structure at a molecular level to allow for chiral interactions, as the fundamental basis for the distinction between enantiomers is the formation of diastereomers or a diastereomeric complex. The chirality in MOFs is typically introduced by using a chiral enantiomer as organic linker or by post synthetic modification (e.g. functionalization of a N-group). An example of the first strategy is $[Zn_2$-(bdc)(L-lac)(dmf)] · DMF where lactic acid (lac) is coordinated to the zinc node (Suh et al., 2012). An interesting approach is the incorporation of metalloligands into the MOF structure. These complexes may function as the bridging linkers, introduce further organic and inorganic active sites of (a)chiral nature. (Das et al., 2012;