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Comparison of structured adsorbents for the adsorptive isolation of food ingredients from large streams

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ABSTRACT

We present guidelines for the configuration of industrial scale chromatographic separation of small molecules. We compared the performance of different axial packed beds, channeled monoliths and a continuous monolith assuming silica as base material. The calculated mass transfer rates were used to calculate the height of a theoretical plate (HETP). The HETP and pressure drop relations as a function of velocity were used to calculate the resultant velocity and packing length for different conditions (efficiency, pressure drop, affinity constant and throughput). The specific productivity of channeled monoliths can be up to 2.5 orders of magnitude higher than that of a packed bed. This implies that at large scales (in which the pressure drops need to be limited, and the flow rate is high), channeled monoliths are preferred since they may reduce the equipment size up to 100 times and the required resin volume up to 1000 times. Accordingly, we demonstrate the potential of channeled monoliths in chromatographic processes but also draw a window pointing out the feasible configurations to use with the highest productivity for a given set of process requirements. © 2015 The Institution of Chemical Engineers. Published by Elsevier B.V. All rights reserved.

1. Introduction

The food industry has an increasing need for large-scale selective separation processes. This is not only to satisfy a growing health awareness and market for functional foods and nutraceuticals, but also to process and add value to low value side streams and waste streams. Most of these streams are typically large in volume (>10 m³/h), and contain only a low concentration (order of g/m³) of target molecules, which typically have a molecular mass of 400–1200 Da. Although chromatographic processes offer the required resolution, it is a challenge to find cost-effective systems with reasonable equipment size and process times.

Fractionation or enrichment of food ingredients using chromatography is normally done using a packed bed. The conventional packed bed of spherical particles presents many drawbacks for processing large streams, such as the pressure drop that becomes a limiting factor when using viscous streams, while streams with suspended solids or components that cause fouling may result in blockage of the column. To minimize this, short and wide (pancake-like) columns or big particle diameters are used in practice; with the exception of radial flow chromatographic configurations in which the width-to-length ratio can be reduced up to a certain extent though keeping the same performance (Besselink et al., 2013). Hence, standard axial chromatography leads to expensive

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Nomenclature

Roman letters

a	Side of the squared open channel (μm)
a_{spec}	External surface area per volume of adsorbent (cm^2/cm^3)
c_i	Feed concentration of a certain component i (g/L)
\bar{C}_M	Dimensionless resistance to mass transfer in the mobile phase
d	System diameter (μm)
d_{disp}	Equivalent dispersion particle diameter (μm) (Leinweber et al., 2002)
d_{perm}	Equivalent permeability particle diameter (μm) (Leinweber et al., 2002)
d_H	Hydraulic diameter of the channel (μm)
d_p	Particle diameter (μm)
D	Column diameter (m)
D_e	Effective diffusive coefficient of the target molecules inside the stationary phase (m^2/s)
D_L	Axial dispersion coefficient (m^2/s)
D_m	Molecular diffusivity (m^2/s)
D_p	Pore diffusivity (cm^2/s)
D_s	Surface diffusion coefficient (m^2/s)
F	Phase ratio: $(1 - \varepsilon_b)/\varepsilon_b$
f	Friction factor (-)
h	Reduced height or contribution to one theoretical plate (-)
HETP	Height equivalent to one theoretical plate (m)
k	Overall mass transfer coefficient (s^{-1})
K	Equilibrium constant of the linear isotherm (-)
k_f	Film mass transfer coefficient (s^{-1})
k_1	Retention factor at infinite dilution: $(1 - \varepsilon_b)/\varepsilon_b \cdot (\varepsilon_p + (1 - \varepsilon_p)K)$
K_p	Hindrance factor for pore level diffusion (-)
L	Column length (m)
N_{plates}	Number of plates (-)
ΔP	Column pressure drop (Pa)
Pe	Péclet number or reduced velocity ($Pe = u \cdot \delta / D_m$) (-)
Q	Flow rate ($\text{m}^3 \text{s}^{-1}$)
Re	Reynolds number (-)
r_o, r_i	Outer radius of an equivalent hollow cylinder used to describe intraparticle mass transfer in the channeled monolith following the LDF (Patton et al., 2004) (μm)
R_p	Radius of spherical stationary phase particles (μm)
Sh	Sherwood number (-)
Prod_i	Specific productivity ($\text{kg}/(\text{m}^3 \text{s})$)
T	Mobile phase temperature (K)
u_o	Superficial velocity (m s^{-1})
u	Linear or interstitial velocity of the mobile phase (m s^{-1}) V Column volume (m^3)
w_c	Corrected adsorbent wall thickness (μm)

Greek letters

α	Aspect ratio of rectangular channels
δ	Characteristic length (μm)
ε_b	External bed porosity: interparticle, interskeleton (equal to $\varepsilon_{\text{macro}}$) (Leinweber et al., 2002; Leinweber and Tallarek, 2003) or channel void (Rezaei and Webley, 2009)

ε_p	Intraparticle or intraskeleton porosity (-)
$\varepsilon_{\text{total}}$	Total column porosity (-)
ψ_B	Constant accounting for the solute-solvent interaction (equal to 2.6 in the case of water) (-)
γ_1, γ_2	Geometrical constants in Eq. (14) equal to 0.7 and 0.5 respectively (Guiochon et al., 2006).
λ_m	Ratio between adsorbate molecule and average pore diameters (-)
μ	Viscosity of the fluid (Pa s)
ρ	Density of the fluid (kg/m^3)
τ_{intra}	Intraparticle or intraskeleton tortuosity (-)

Subscripts

A	Related to the solute
B	Related to solvent
ax	Related to axial dispersion
ext	Related to external mass transfer
$intra$	Related to intraparticle mass transfer
$macro$	Related to macropores (bigger pores)
$meso$	Related to mesopores (smaller pores)

columns or low productivities and efficiencies as a result of the long diffusive lengths (particle diameters) needed. The resulting chromatographic process cost is generally not compatible with the relatively low economic value of food products (e.g. compared with pharmaceuticals). Therefore the food industry needs more efficient adsorbents to reduce cycle times, pressure drop and equipment cost while maintaining or improving the productivity and column efficiencies.

Over the last half century, new chromatographic media have emerged. The so called monoliths, one-piece porous structures with interconnected pores or channels have found already their place in different applications. In the pharmaceutical sector generally polymeric continuous monolithic rods, and an up-scaled version of these monolithic rods to be run in radial flow mode, have been evaluated (Jungbauer and Hahn, 2003). In the field of High Performance Liquid Chromatography (HPLC) organic (polymeric), silica and hybrid organic-silica structures have been applied for analysis purposes (Guiochon, 2007; Jungbauer, 2005; Jungbauer and Hahn, 2008; Merhar et al., 2003; Svec and Lv, 2015) reducing the analysis times and yielding higher resolutions. In catalysis and gas (preparative) applications, structures in the shape of “honeycombs” (or channeled monoliths) and foams have been used, and these structures usually consist of a metallic or ceramic support in which a catalyst is either immobilized or on which a washcoat is applied on its inner surface.

Non-particulate adsorbents leading to more optimal adsorption are discussed in literature for gas-phase adsorption (Crittenden et al., 2005; Patton et al., 2004; Rezaei and Webley, 2009, 2010) and for heterogeneous catalysis (Akhtar et al., 2014; Vergunst et al., 2001). The main advantage of these structures is a lower pressure drop combined with a higher mass transfer rate. In the case of channeled monoliths, mass transfer may still be a limitation with thick walls or low cell densities, but monoliths with very high cell densities and thin walls have been made. Indeed, these materials show an excellent combination of low pressure drop and high productivity (Li et al., 2009).

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