Journal of Chromatography A, 1335 (2014) 122–135

Contents lists available at ScienceDirect

Journal of Chromatography A

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

Review

# Segmented flow and curtain flow chromatography: Overcoming the wall effect and heterogeneous bed structures

Ross Andrew Shalliker[a,*], Harald Ritchie[b]

[a] Australian Centre for Research on Separation Science (ACROSS), School of Science and Health, University of Western Sydney (Parramatta), Sydney, NSW, Australia
[b] Thermo Fisher Scientific, Manor Park, Tudor Road, Runcorn, UK

ARTICLE INFO

*Article history:*
Received 11 July 2013
Received in revised form 31 July 2013
Accepted 1 August 2013
Available online 6 August 2013

*Keywords:*
Parallel segmented flow
Curtain flow
Bed heterogeneity
Efficiency
HPLC
The wall-effect

ABSTRACT

The variation in mobile phase velocity as a function of the column radius has been shown to be a major limitation in the efficiency of HPLC columns. One contributing factor to the variability in the flow velocity stems from the heterogeneity in the radial packing density, leading to what has been described as the 'wall-effect'. The wall-effect generates parabolic-type elution profiles, which dilutes the sample and creates tailing bands. In this communication a new column technology is discussed that has been designed to overcome the wall effect, minimising the limitations associated with packing heterogeneity. This technology has been referred to as active flow technology and consists of two types of column designs, parallel segmented flow and curtain flow. In both these column designs sample that elutes through the column in the radial central region of the bed is separated from the flow that elutes along the wall region. Hence, the sample that elutes through the most efficiently packed region of the bed is collected to the detector. As a consequence more theoretical plates are obtained, and sensitivity is increased since the sample is not diluted by the diffuse tail. Sensitivity is enhanced further in the curtain flow design. The benefits of these new columns are discussed



**Contents**



* Corresponding author. Tel.: +61 2 9685 9951; fax: +61 2 9685 9915.
*E-mail address:* r.shalliker@uws.edu.au (R.A. Shalliker).

0021-9673/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.chroma.2013.08.004

## 1. Introduction

The birth of modern HPLC arose from a transformation of rudimentary open-tubular chromatography columns into more sophisticated slurry packed columns prepared by pressure consolidation. It is difficult to define the exact point in time at which modern HPLC was established since along with the application of pressure packing techniques came a decrease in the size of particles that could be employed for these more efficient modern columns. To our reckoning, however, we believe that the birth appears to originate from the works of Scott and Lee [1] in 1969, where they packed columns using 10 μm ion exchange media in a downward slurry high pressure system. These early high pressure slurry packing methods were a development from the 'tap and fill' dry packing methods of earlier days where larger particle sizes in the order of tens of microns or more were employed.

### 1.1. Physical evidence of column bed heterogeneity

#### 1.1.1. End column detection

It seems, however, that even from the early days of modern HPLC chromatographers were aware of aspects in heterogeneous packing distributions and the ramifications that such variations had on the efficiency of the separation process. Although undertaken in columns that were dry packed, Knox, Laird and Raven [2], performed a series of careful experiments that involved the measurement of chromatographic band profiles at various radial locations at the end of the chromatography column. The column was packed with ~21 μm diameter particles, and sample was introduced into the column using a central point injection technique, based on their earlier study [3]. Band profiles were recorded using a polargraphic detector whereby the electrodes could be placed at precise radial locations at the end of the column packing material. Their studies revealed that as the solute band neared the wall, the reduced plate height decreased, gradually at first (from the radial centre towards the wall), but then abruptly at the wall. The reduced plate height ($h_{axial}$) in the column centre was 1.7, but 1 mm from the wall $h_{axial}$ had increased to 4.7. There was also an increase in flow velocity as the wall was approached with the authors expecting that there was a high likelihood of a rapid increase in flow velocity very near the wall, although they could not measure this. The notion of a 'wall-effect' in chromatographic columns can largely be attributed to these early works of Knox et al. [2,3], although Golay [4] reported earlier, variations in flow velocities as a function of radial location in chromatographic beds, but never investigated the effect further.

Later, following recognition of probable 'wall effects', Eon [5] undertook further studies to elucidate the complexities of the wall effect. It is worth noting that in 1978 Eon commented that despite the great amount of attention being paid to column performance the nature of the wall effect was poorly understood, indeed, such is the complexity of the wall effect, it has been the focus of continued research for more than 40 years. In the study by Eon [5] the migration efficiency of solutes through rigid wall columns was compared to the migration efficiency in columns with radially compressed walls. His findings in relation to the variation in reduced plate height and flow velocities as a function of the radial flow stream traversed by the solute was in general agreement with Knox et al. [2]. He also showed that the 'wall effects' could be mediated quite significantly by using soft-walled columns that could be compressed. This was one of the earliest studies providing evidence that described the concept of radial compression columns, details of which will be covered later in this text.

Although these early studies on dry packed columns highlighted the nature of wall effects, they nevertheless did not represent aspects of solute migration that might be observed in high pressure slurry-packed columns using small particles. A decade after the first works conducted by Knox et al. [2], Baur and Wightman [6] used a microelectrode as a localised 'end-column' detector on commercially prepared columns packed with 3 μm particles. Using this type of detection process they were able to provide substantial evidence that the reduced plate height increased significantly as the wall was approached. For example, on a 4 cm long column the reduced plate height measured in the radial centre of the column was 1.9, while 1 mm from the column centre the reduced plate height was 4.2. In contrast to the findings of Knox et al. [2] and Eon [5] who both studied dry packed columns, Baur and Wightman [6] observed that the flow velocity decreased as the wall region was approached; the retention time was 5% greater near the wall. The solute concentration on these 4 cm long columns was also highest in the column radial centre. However, as the column length was increased to 10 cm the gains in efficiency were somewhat mediated.

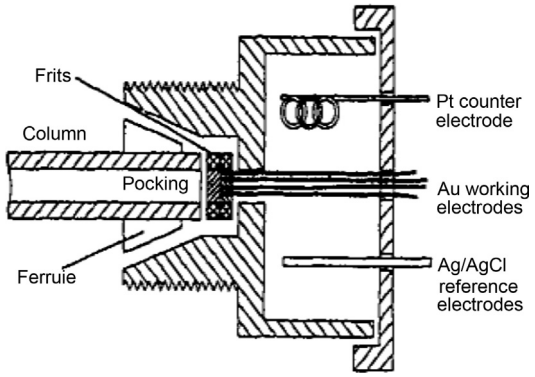


**Fig. 1.** Schematic diagram of the end column detector comprising four gold working electrodes, a platinum counter electrode and a reference electrode. The gold working electrodes are housed in a frit, which is pressed against the frit at the column outlet. The electrode frit can be rotated to expand the area of detection.
(Reproduced from reference [7] with permission).

Even though these early works [2–6] showed that column beds were radially heterogeneous, especially near the wall, and related to some type of wall effect, mainstream chromatographers were not too concerned with its consequence, since it was deemed to be minor with respect to the averaged column performance and the overall separation power afforded by the rapid gains in separation technology experienced since the birth of modern HPLC. Studies on the wall effect and in general bed heterogeneity were as a consequence undertaken by just a few. Five years after the work of Baur and Wightman [6] the next important study on bed heterogeneity was undertaken by Farkas, Chambers and Guiochon [7]. They used an array of micro electrodes at the end of the column to investigate the wall effect: Four gold electrodes were embedded into a frit at accurately known radial locations, as illustrated in Fig. 1 [7]. One electrode was near the column centre, two others at approximately half the distance to the column wall and the forth electrode was close to the wall. The frit that housed these electrodes was of the exact same dimensions as the frit at the end of the column packing. Hence the electrode frit could be rotated to allow end-column detection across various diameters of the column. In total, the experiment testing the efficiency of solute migration through the bed was repeated four times with the electrode frit rotated approximately 90° each time, yielding 16 data points across the column cross-section.

Farkas et al. tested a number of columns, most were homemade and packed with either 40 μm glass beads, or 10- or 16 μm silica particles, while one was a commercial C18 silica column packed with 16 μm particles. They found that the velocity was systematically lower near the wall than in the centre of the column when packed with the 40 μm glass beads, but there was