An Introduction to the Concept of Monodensity in Silica Particles and its Effect on Chromatographic Performance

by John P Hanrahan, Tom O' Mahony, Ricky Curley, John J Hogan & Joseph M Tobin
Glantreo Ltd, ERI Building, Lee Road, Cork T23 XE10, Ireland.
Tel: +353 21 4901965. Email: j.hanrahan@glantreo.com

Have you ever imagined what the inside of fully porous or a superficially porous silica particle looks like? Traditionally the internal structure of a silica particle has been considered to be a homogeneous arrangement of pores with little or no imperfections. However this is not the case. On examination of several different silica particle types from a range of silica manufactures we have found that the majority of porous silica particles currently on the market contain significant internal voids or holes. These voids are clearly visible under a Scanning Electron Microscopy (SEM) after the particle has been manipulated using Focused Ion Beam (FIB) milling technology. These voids can be up to an order of magnitude larger than the claimed pore size of the silica. The presence of these voids or holes suggest that the particles are not monodense, i.e. there is a significant density distribution across particles. Theoretically these holes or voids could cause mass transfer issues which could lead to peak broadening, peak tailing and ultimately losses in chromatographic efficiency. Within this article we aim to introduce the concept of 'monodensity' which for years has been spoken about within the silica community but to date has not been published on. This article will also study the effect of monodensity by chromatographically comparing Glantreos SOLAS™ MonoDense™ particles with commercial particles known to contain voids.

Introduction

Traditionally, silica manufacture has been based on the hydrolysis of an alkyl silicate in the presence of an acid or base in solution or gas phase. Several detailed reviews have been written on the different manufacturing processes of silica particles. These manufacturing approaches can be broken into different sub sets as illustrated in Figure 1. An in-depth discussion on the pros and cons of each process is well beyond the scope of this article, although several very good review articles exist for the interested reader [1,2]. Glantreo has concentrated on liquid sol gel routes to the production of monodisperse and more recently monodense particles, in particular we have utilised the modified Stöber process as our platform manufacturing process for the production of fully porous and superficially porous silica particles. In order to understand the rational for basing our process around this modified Stöber process a brief background is beneficial.

Non Porous Stöber Particles

In 1968, Werner Stöber et al. [3] reported a process for the controlled growth of
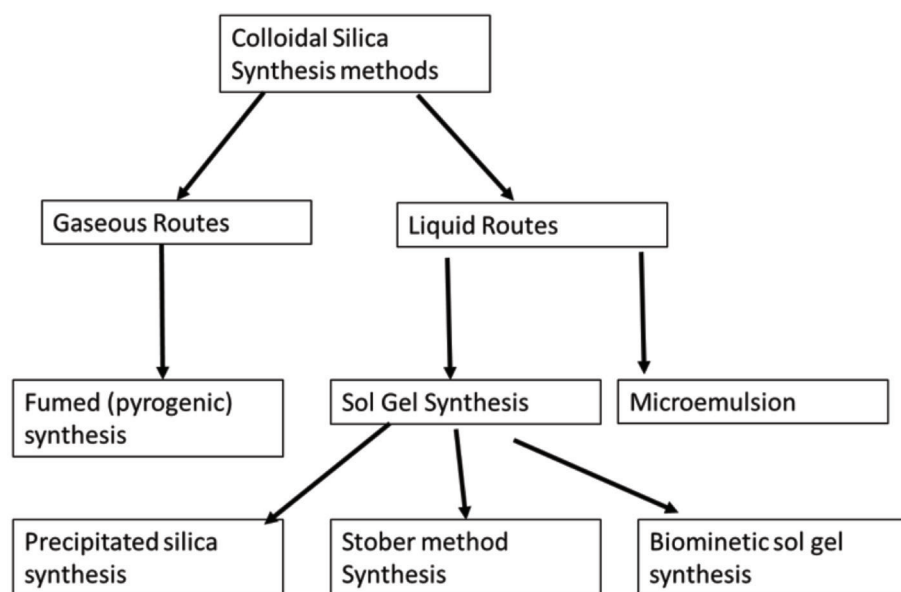

Figure 1. Schematic representation of industrial silica manufacturing routes.

spherical non-porous silica particles of uniform size. The particles obtained via this method ranged in size from 50 nm to 2000 nm in diameter. The relatively simple procedure involves mixing a silica precursor, in the form of an alkyl silicate, with ammonia in a water/alcohol solution. The alkyl silicate is hydrolysed to give silicic acid, which subsequently condenses to give the monodisperse silica particles. Ammonia is used as a base catalyst and influences the morphology of the particles in a manner which produces spherical particles. A key aspect of the Stöber process is the ability to produce different particle sizes by altering the reaction conditions, i.e.,

temperature, type of alcohol/alkyl silicate and concentrations of the various reagents. However, the Stöber process only produces non porous particles. In an attempt to develop porous particles which, have a larger surface area which is a desirable commodity for stationary phases within HPLC for small molecule separations, several research groups began investigating the addition of surfactants or porogens to the Stöber process [4,5]. This, they hoped would combine the properties of monodispersivity of the original Stöber process with the porosity required for a HPLC stationary phase. This addition of porogens has been termed the modified Stöber process or modified Stöber Fink Bohn (mSFB) process.

Modified Stöber Process to yield Porous Particles

The 'modified' Stöber system consists of five reagents namely an alkyl silicate, water, an alkaline catalyst, alcohol and a surfactant or porogen. By empirically relating the initial synthesis conditions to the final product, silica particles with varying morphology and particle size have now been produced Thus, particle and pore size (after subsequent removal of the porogen from the silica) may be 'tailored' by relating reactant stoichiometry and experimental conditions to the final silica properties rather than trying to design through an understanding the complex physical and chemical processes involved. In general, 'tailoring' both the particle and pore size of monodisperse precipitates and porous materials has progressed in this manner. Grün & Unger et al. [4] pioneered work into mSFB reactions. In 1992, Mobil Corporation also worked on a new family of silicate molecular sieves (M41S) which could also be considered a modified Stöber process. However, there are some major short comings of the modified Stöber process and the particles it produces. These shortcomings have hampered its uptake as a stationary phase for HPLC, for example the largest particle size obtainable with this type of process is in the sub 5 µm range. The pore size of as synthesised particles tends to be in the 20 Å range therefore subsequent pore enlargement steps are required. Synthesis is carried out in an alcoholic solvent and hence large scale production might be considered expensive. Also having a stationary phase of highly monodisperse particles (SD < 5%) can cause significant increase in backpressure compared to a packed bed of 'less' monodisperse particles. Glantreo has

developed a number of processes which address these issues and have also developed a process that produces particles free from voids or holes within the particle sub structure. Particles that are free from voids in the particle sub structure are expected to reduce band broadening, the more homogenous nature of the partuile may also facilitate the easier packing of these materials.
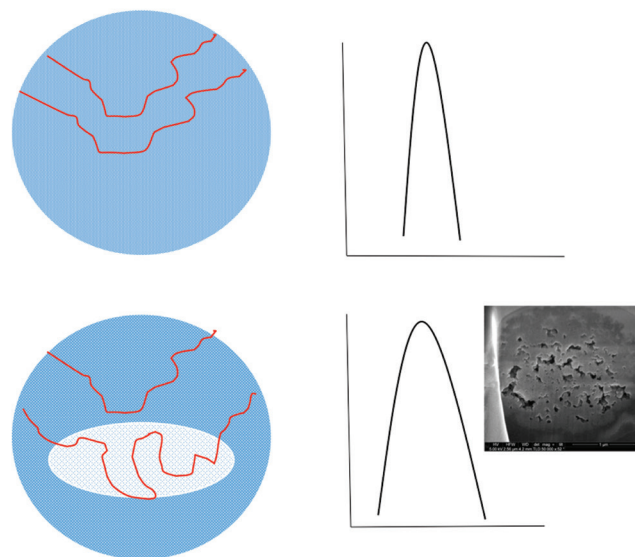

Figure 2. Schematic representation analyte diffusion paths within a monodense and voided particles and subsequent effect of chromatographic performance.

The concept of Monodensity

Until now it was assumed that the internal porous structure of silica particle was homogeneous. However detailed work at our laboratories has shown this not to be the case. Whilst the idea of monodispersivity is known and accepted within the silica manufacturing and chromatographic communities, hardly any literature exists on the concept of monodensity (i.e. a uniform or homogeneous distribution of pores within a silica particle) in silica particles. A recent submission to International Symposium on Capillary Chromatography (ISCC) was noted but further details could not be found [6]. On communication to the wider chromatographic community and silica manufacturing community it would appear the concept of Monodensity is known but 'swept under the carpet' to some extent. This may be for several reasons;

(a) FIB which allows the dissection and imaging of the interior silica particles has only recently become a main stream analytical tool thereby allowing material scientists to peer into the internal structure of the silica particles.

(b) Manufactures of silica particles may know about the voids within the silica particles but chose not to disclose it to the scientific community. There may be valid reason for this, as realistically with a technique like FIB only a small number of particles can be examined hence it may be hard to draw statistically relevant conclusions.

(c) Whilst it may be relatively easy to separate large particles (>3µm) via air classification. The large scale economics

of being able to separate particle by density via liquid elutriation is not a trivial matter.

Monodensity and its effect on chromatographic performance

Theoretically it is suspected that a more homogeneous pore structure within a silica particle should lead to better mass transfer properties thereby reducing the C term of Van Deemter equation. For a voided particle, it is envisioned that an analyte may become 'trapped' within the void of the particle for a significant time and hence lead to band broadening as depicted in Figure 2. Due to the lack of subject matter on the concept of monodensity or even on the pore size distribution effects, no quantifiable data exits. SOLAS™ MonoDense™ is shown to have certain beneficial chromatographic properties owing to this monodense or homogeneous pore structure where in the manufacturing a dual phase surfactant system was employed and have modified several of the traditional processing steps in an attempt to limit and prevent this voiding issue.

Within this paper the aim is to;

(A) Introduce the concept of monodensity

(B) Analyse four commercially available silica's via FIB

(C) Prove the existence and characterise the void structures observed within silica particles

(D) Chromatographically compare a 2 µm SOLAS™ MonoDense™ C18 with other 2 µm C18 columns that are known to contain voided particles.
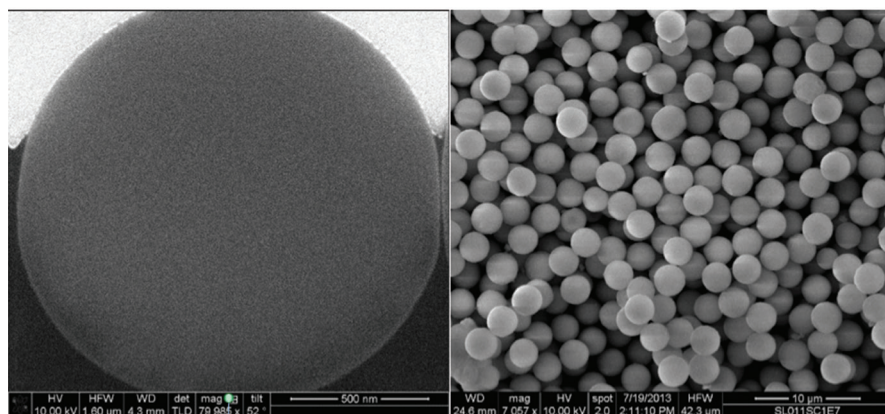
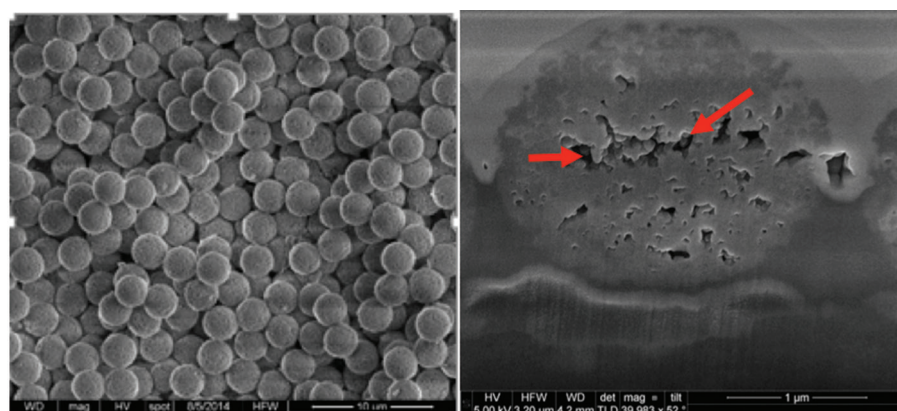Figure 3. SEM and FIB images of SOLAS monodense particle

Figure 4. SEM and FIB images of manufacturer A particles

(E) Examine several core shell or superficially porous particles (SPP) to understand if the voiding phenomenon is also observed in this particle class.

(F) Outline some of the potential causes of these voids.

Experimental

Scanning electron microscopy (SEM) was carried out on a FEI Inspect F instrument operating at 10 kV. Silica samples were placed on conductive carbon tape prior to analysis. Focussed ion beam (FIB) was performed using a FEI Helios Nanolab 600 dual-beam FIB. The electron beam was operated at 5 kV with the ion beam operating at 30 kV for Pt deposition and thinning. The cross sections were prepared using a focussed ion beam method [7].

Nitrogen gas was used to probe the pores of the silica particles. The volume, diameter and size distribution of the pores can be determined by nitrogen sorption measurements. The sorption analyses were performed on a Micromeritics Tristar II surface area and porosity analyser. Prior to analysis, each sample was de-gassed for three hours at 400°C and measurements were performed at -169.15°C (77 K). The surface area was determined using the BET (Brunauer-Emmett-Teller) method. The pore volume, pore diameter and pore size distribution were determined using the BJH (Barrett-Joyner-Halenda) method [8].

SOLAS™ MonoDense™ particles are manufactured via a modified Stöber process, the particulates of this process and subsequent bonding and packing protocols are proprietary to the company. The company uses a proprietary two phase surfactant system to yield particles with little or no voids present.

LC performance testing was carried out on an Agilent 1200 LC system. Flow rates between 0.025 and 1.2ml/min were employed. Column dimensions used were typically 2.1 x 50 mm. Comparison between the plots of the reduced HETP, h versus the reduced linear velocity, v, of naphtho[2,3-a] pyrene for three columns packed with 100 Å 1.7 µm particles. Plots were fitted after correction from the extra column band broadening

Results

FIB analysis and imaging of 'Voids' in FPP particles

Figure 3 illustrates SEM and FIB images for SOLAS™ MonoDense™ sub 2µm particles. The SEM images shows a relatively monodisperse particle size distribution (d90/d10 = 1.4 as measure by Elzone data not shown). Analysis of the FIB images shows that SOLAS™ MonoDense™ has a homogenous substructure within the particle. The 10 nm pores are just about visible and are evenly distributed within the particle. This type of particle can be considered monodense. In comparison to this homogeneous internal pore structure, Figures 4, 5 and 6 illustrate silica particles from other silica manufacturers. Figure 4 shows a commercially available 1.9 µm monodisperse (d90/d10 = 1.2) fully porous particle and on inspection of FIB images it is clearly evident that large voids exist are clearly noted throughout the particles, highlighted by red arrows. The centre of the particle appears to contain the majority of the voided space. An elongated voided path through the middle of the particle is noted. In the interest of brevity only one FIB image is shown, however FIB analysis was conducted on approximately 10 particles per batch in an attempt to yield statistically relevant information. All physical properties for silica examined in this study are shown in Table 1.

Table 1. Physiochemical properties of FPP studied.

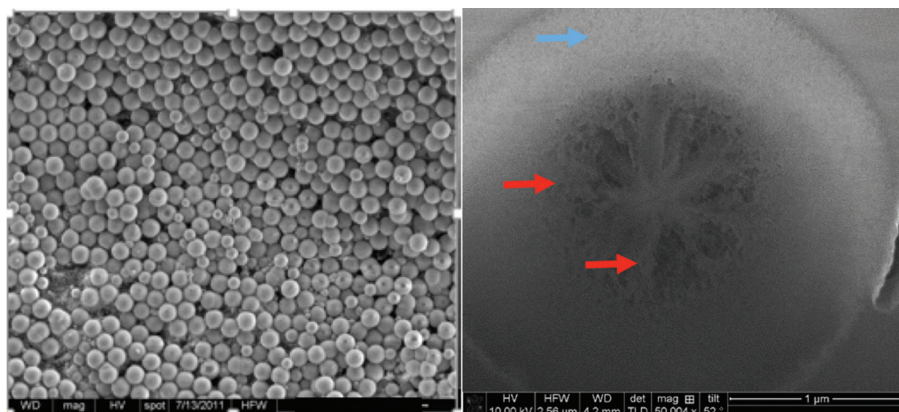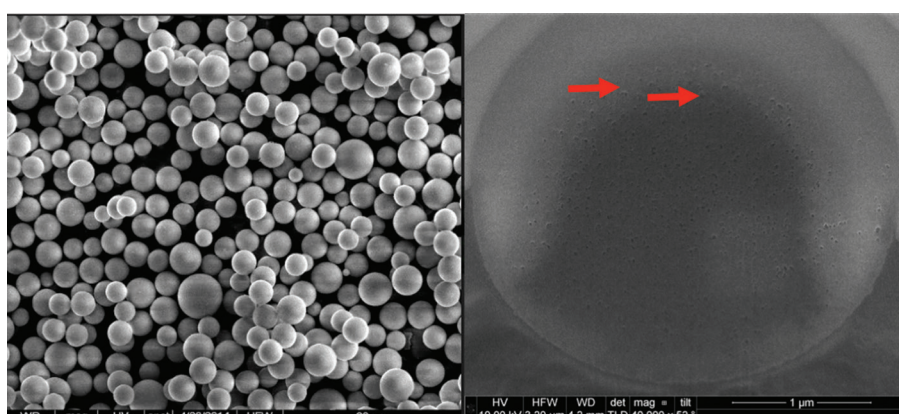| Silica Type	Particle size (µm)	Monodispersivity (d90/d10)	Surface area (m²g⁻¹)	Pore Volume (cm³g⁻¹)	Pore Diameter (Å)	Type of Voids noted
SOLAS™ Monodense™	1.8	1.4	300	0.60	80	None
Manufacture A	1.9	1.2	245	0.63	93	Mixture of Large and small voids.
Manufacture B	1.9	1.5	200	0.50	110	Starburst Crater in centre with homogeneous pore on corona
Manufacture C	1.9	1.5	315	0.7	120	Homogeneous void structure

Figure 5. SEM and FIB images of manufacturer B particles

Figure 6. SEM and FIB images of manufacturer C particles

calcination/ porogen removal may cause mini explosions within the particles. Particularly at the centre of powders.

(F) Collapse of thin walls during calcination/ porogen removal

Chromatographic Analysis

Figure 7A is the van Deemter plot of the reduced HETP vs the reduced linear velocity for the SOLAS™ MonoDense™ C18 column and two commercial brands of C18 packing in a 2.1 ID x 50 mm column after subtraction of extra column broadening due to the instrument. The experimental coefficients of the HETP plots obtained from the SOLAS™ MonoDense™ C18 and the two commercially C18 packed columns are given in Table 2. The parameters that contributed to band broadening according to the van Deemter equation revealed some interesting results when comparing the mass transfer properties of the SOLAS™ MonoDense™ C18 columns to the commercial brand of columns Figure 7 illustrates the chromatographic performance of the SOLAS™ MonoDense™ C18 against manufactures A and B. Two observations are quite quickly noted from the Van Deemter plots and back pressure profiles. These are namely (a) The C term in the van Deemter for SOLAS™ MonoDense™ tracks downwards at higher flow rates suggesting better mass transfer properties for this type of particle. (b) The van Deemter for Manufacturer B which contains large star burst voids shows a large increase in the C term. This phenomenon is well known which offers some proof to the theory that a large void space within the particle can cause dispersion issues.

A review of Table 2, shows that the experimental A-term for the column from manufacturer B is the smallest (0.17), suggesting that it is the best packed column for this study. This assumption was made by taking into account the generality of the intrinsic surface roughness of the particle. Having, a rough surface tends to improve the packing quality. This can be promoted by the large coefficient of shear friction that takes place between the rough particles of the silica during the slurry packing process, requiring a large amount of stress to be applied to the growing packed bed. Because of the roughness on the surface of the particles, less slippage is encountered on depressurisation of the column after packing, thus keeping a homogeneous packing and ultimately contributing to a reduced A-term. Conversely, the particles

Figure 5 illustrates SEM and FIB images from a 'traditional' sub 2 μm particle with a relatively large particle size distribution (d90/d10 = 1.5). A large starburst void is noted within the particle substructure. The void is concentrated in the centre of the particle (highlighted by red arrows). A more uniform homogeneous structure of the pore is noted on the outside corona (blue arrows) of the particle. On examination of the physical property of this samples this sample is seen to have a relatively low surface area (200 m^2g^{-1}) and average pore volume (0.5 cm^3g^{-1}).

Figure 6 shows another SEM and FIB image for a traditional polydispersed (d90/d10 > 1.5) 2 μm silica particle. In this case an almost homogeneous network of voids is observed throughout the particle. The physical properties of this this silica are as follows, surface area 315 m^2g^{-1}, pore volume = 0.7 cm^3g^{-1} and pore diameter 120 Å. This material contains voids which seem to be homogeneous and consistent throughout

the particle. Indeed, it could be interpreted that whilst the monodispersity of these particle isn't the best the homogeneous nature of the voids may counter act any losses in efficiency.

Without knowing the specifics of different manufacturing method to produce the above particle types it is difficult to postulate a reason for these voids. Several different reasons may be hypothesised at this stage;

(A) Presence of impurities within reaction solvents e.g. dust

(B) Presence of emulsion droplets with reaction mixture

(C) Variation in hydrolysis rate of silica precursors

(D) Impure porogens or surfactant/ polymers with large molecular weight distributions leading to the presence of micoremulsion droplets with the liquid

(E) Localised heating effects during

Table 2. Van Deemter Coefficients

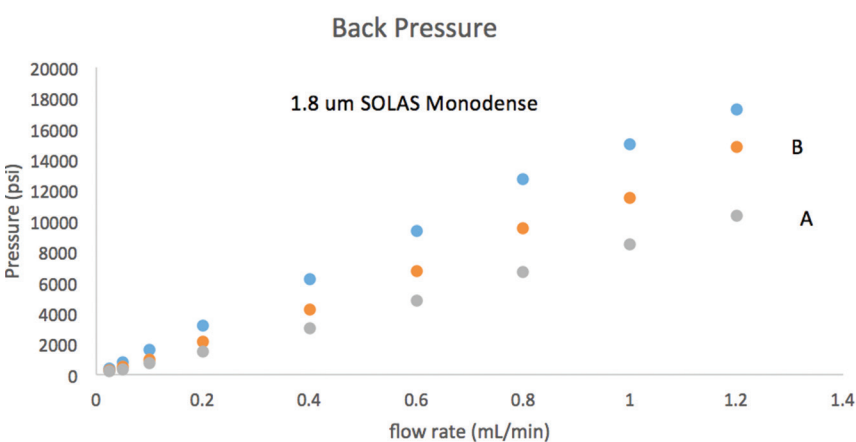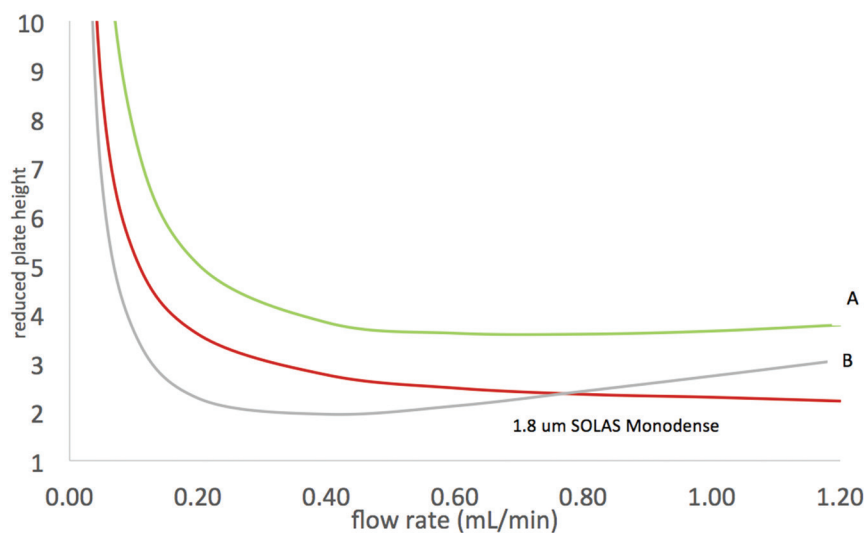| Columns	Solas™ Monodense™ 1.8um C18	Manufacturer A 1.9 C18	Manufacturer B 1.9 C18
A Term	1.87	1.89	0.17
B Term	4.85	7.89	5.33
C Term	0.005	0.091	0.147

Figure 7. Van Demeter and back pressure profile for Manufacture A (A) Manufacturer B (B) and SOLAS Monodense 1.8 μm
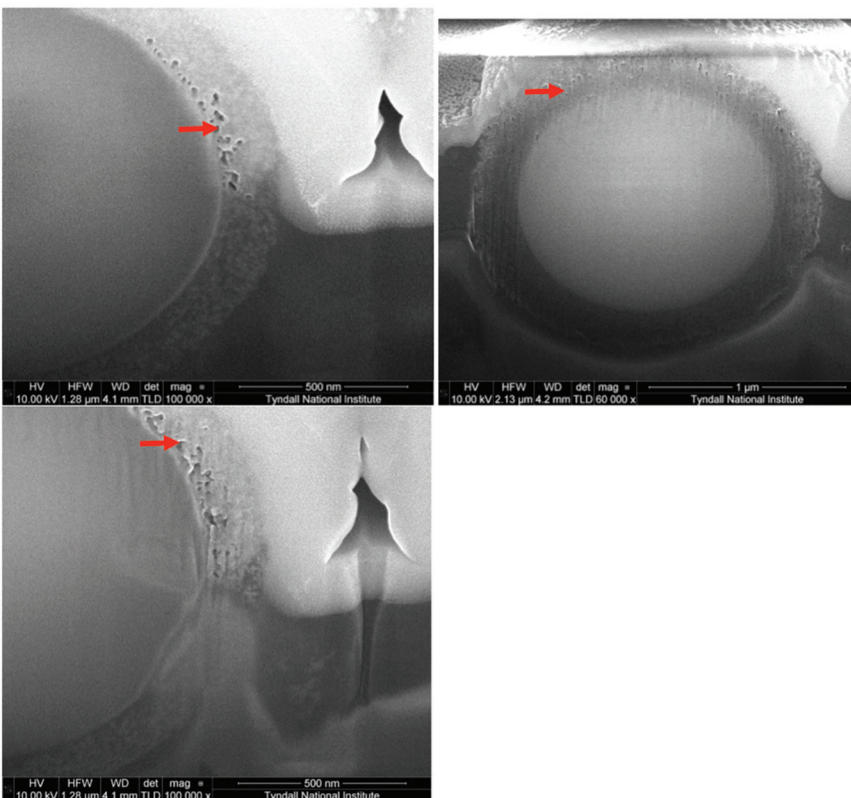

Figure 8. FIB images of several core shell particles

with smooth surface tends to slip quickly and results in a rapid change in bed strain, causing a more heterogeneous packing consisting of large variation in the local value of external porosity and resulting in a large A term.

The B term contribution to band broadening on the Manufacturer A-C18 column was the largest (7.89) amongst the three columns. In the linear velocity region where the B-term is significant, the solute will spend more time inside the column and diffuse axially resulting to distortion of the solute band. The Solas™ Monodense™ has the smallest B term coefficient (4.85) compared to the other two columns.

The C term coefficient for Solas™ Monodense™ was the lowest at 0.005. This effect can be ascribed to the homogeneous nature of the pore structure leading to shorter solute diffusional path in and out of the particle substructure. An analysis of the backpressure plots for Solas™ Monodense™ and the other 2 commercial columns is shown in Figure 7B it is evident that the backpressure for monodense particles is higher than that of traditional particles as seen in Figure 7B, possibly due to the slightly smaller particle size of the Solas Monodense particle.

Other benefits of monodense particles

Due to the monodense nature of the particles, it has been shown that the packing of these particles is somewhat easier than with traditional silica's, resulting in a reduction in the number of columns that fail to pack. This is most likely due to the homogeneous distribution of particles within the packing solvent with little or no flocculation or settling of particles during the packing process. Early results have shown a reduction of almost 10% of scraped or failed columns. From the production of large amounts of columns this could represent a significant cost saving.

Voids in Superficially porous (Core Shell) particles

The issue of voids is not a problem confined to fully porous particles (FPPs), it is also observed in core shell or superficially porous particles (SPPs), as can been seen in Figure 8. Whist the process for the manufacture of core shell particles is different to that that utilised in the manufacture of FPPs, several steps are transferable between the two. For example condensation and hydrolysis

of silica precursors as well as calcination of porogens at high temperature etc. It is expected that these similar steps in the manufacture of SPP will also lead to the presence of voids within the shell of silica particles.

Conclusions

Due to the unique homogeneous pore structure of SOLAS™ MonoDense™ separations are possible at faster flow rates without compromising efficiency as shown above in van Deemter plots. A slightly higher back pressure is noted for SOLAS™ MonoDense™ particles possibly due to the fact that no large voids or pores exist within the particle. Commercial silica that contain 'large starburst' voids show a dramatic increase in the C term.

By comparison, particles that have monodense structure and contain a homogeneous internal pore structure leads to the efficient transfer of analytes into and out of the silica pore structure, thereby leading to more efficient and effective chromatography. Additionally, the Glantreo particles represent a media that is easier to pack with a reduced failure rate in packing.

From FIB-SEM analysis of core shell particles it would seem that this phenomenon also exists with the SPP particle class. This monodensity issue may explain why some particles with remarkably similar physiochemical properties [e.g. surface area, pore size, pore volume particle size and particle size distribution, carbon coverage etc.] may behave so radically different when packed into a chromatographic column.

Acknowledgments

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