

Production of Spherical Aerogel Microparticles by Supercritical Extraction of Emulsion

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Due to high surface area, low density, open pore structure and excellent insulation properties aerogels were intensively investigated in the past decades for diverse range of applications. The state of the art of aerogel production by supercritical drying is to produce monolithic aerogel, where the sol is aged in molds and dried by extraction with supercritical CO₂. Aerogels in form of spherical microparticles would be beneficial for many applications, for instance as a drug carrier in pharmaceuticals, where aerodynamic plays an important role in case of inhalation route, or as insulating materials where homogeneity and flowability is an issue. Because of aerogel's mechanical properties it is difficult, rather impossible to obtain spherical microparticles by milling or crushing of the monolithic or bulk aerogel. This work suggests a new method to produce biocompatible aerogel microparticles using emulsion technique (insitu production). Water in oil emulsion was produced by mixing the sol (dispersed phase) with a vegetable oil (continuous phase) followed by the gelation of the aqueous phase. The size and shape of the gel particles is controlled by the agitation (agitator form and speed). Gel-oil emulsion was subsequently extracted with supercritical CO₂. Two examples of this process are given: silica and alginate aerogels. Silica aerogel spherical microparticles with a surface area of 1100 m²/g and different mean particle diameters ranging from 200 µm to few millimeters were produced. In case of alginate aerogel the oil phase was separated before the drying step to convert the hydrogel into alcogel before CO₂ supercritical drying. This process result in the highest surface area known for similar alginate aerogels (400 m²/g) with a particle mean diameter of 100 µm.

Key word: Spherical aerogel, emulsion, supercritical drying, alginate aerogel, silica aerogel

1. INTRODUCTION:

Microspherical shape particles are highly desired in diverse industries, they can be produced using different techniques. These techniques are usually based on three main processes: solvent extraction/evaporation of emulsions, phase separation (coacervation) and spray-drying [1]. Because of the sensitivity of the sol-gel process none of these processes are suitable for direct aerogel production. However with some modification it is possible to overcome the obstacle of each process. Spray-drying is a strait forward method resulting in a high throughput, but is not suitable for temperature-sensitive compounds. Moreover, control of the particle size is difficult, and yields for small batches are moderate [2]. In case of aerogel production, the solvent evaporation would lead to high capillary forces, as a result, the nanostructure of the gel will collapse. This problem can be solved by spraying the sol into an autoclave at supercritical conditions [3], [4]. Emulsion is a well known process, allowing to produce large amount of microspheres in a robust and controlled manner. Still, the phase

separation is a difficulty for the aerogel production. Thus, a modification of this process is required to overcome this challenge [5].

The aim of this work is to modify the solvent extraction from emulsions in a way which enables the production of aerogel particles in form of microspheres with controlled particle size distribution. Supercritical extraction of emulsions is suggested for this purpose.

The process suggested in this work consists of four basic steps: (1) preparation of the disperse phase by sol-gel process or by dissolution of the gel matrix material in an aqueous phase; (2) emulsification of the aqueous phase in a continuous phase (immiscible with the first one); (3) cross linking/gelation reaction within the dispersed phase (liquid microdroplets) to form stable gel microspheres; (4) CO₂ supercritical extraction of the emulsion to obtain the final microsphere aerogel particles. These steps are schematically represented in Figure 1.

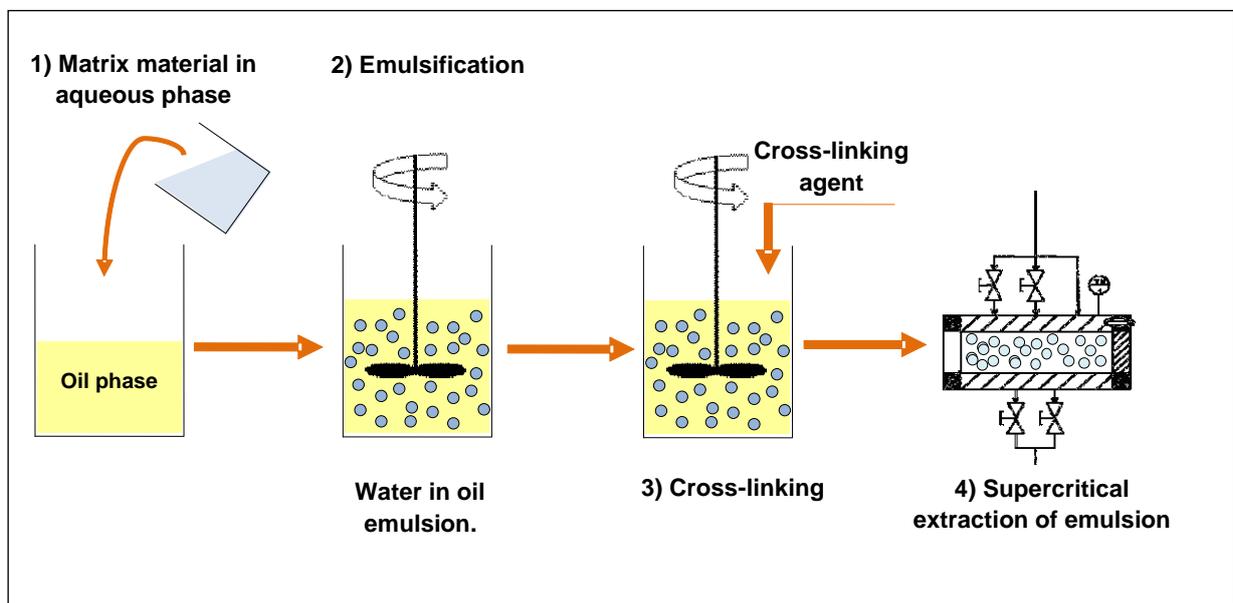


Fig. 1: Schematic overview over the four main steps in aerogel microsphere preparation by supercritical extraction of emulsions.

In some preparation the dispersed phase (aqueous phase) might be not extractable by supercritical CO₂, for such a situation a solvent exchange should precede the extraction step.

2. EXPERIMENTAL METHODS

2.1. Reagents

Carbon dioxide with a purity of 99.9% was supplied by AGA Gas GmbH, Hamburg. Tetramethoxysilane (TMOS) 98% were purchased from Fluka Germany, methanol 99.5%, hydrochloric acid 30% and ammonia hydroxide 25% were purchased from Merck Germany. Na-alginate (63944) was obtained from Riedel-de Haën, Ethanol (p.A.), CaCl₂ (p.A.) were purchased from Merck. All chemical were used as provided without any further processing.

2.2. Methods

2.2.1. Preparation of the gel microspheres

Preparation of silica gel microspheres

Silica sol was produced following the two step sol-gel process [7]-[10]. In the first step tetramethylorthosilicate (TMOS), methanol, water, and hydrochloric acid were mixed together with a molar ratio of:

1 mol TMOS: 2.4 mol MeOH: 1.3 mol H₂O:10⁻⁵ mol HCl.

The mixture was stirred at room temperature for 30 min. After that additional water and ammonia solution were added, to obtain the following molar ratio:

1 mol TMOS: 2.4 mol MeOH: 4 mol H₂O: 10⁻⁵ mol HCl: 10⁻² mol NH₄OH.

Then the mixture was diluted with ethanol to obtain the desired density of the aerogel and stirred for further 3 minutes.

Emulsification of the silica sol in an oil phase

Canola oil (continuous phase) were placed in a 500 ml vessel and mixed using propeller mixer with the desired revolution. The sol (aqueous phase) was then poured at once into the oil phase. Subsequently microsphere droplets were formed. Within 20 min gelation took place and the sol droplets converted to gel spheres. At this stage the mixing can be stopped. After that the gel spheres were left overnight in the oil phase for aging. Different types of the mixer were used as well as different revolutions speed in order to control particles shape and size.

Preparation of alginate gel microparticles

2 wt% of Na-alginate solution was prepared by mixing alginate salt with deionized water. To insure the homogeneity the solution were stirred over night with magnet stirrer [11].

Emulsification of Na-alginate solution in an oil phase

200 ml of Canola oil (continuous phase) were placed in 600 ml vessel and mixed using 4-blades radial stirrer with the desired revolution. 100 ml of Na-alginate solution (dispersed phase) was then poured slowly into the oil. Microsphere droplets were then formed. At this stage 100 ml of aqueous 0.24 M CaCl₂ (cross linker) was added to the emulsion. After 30 min the alginate microparticles were filtered and placed in a successive 10%, 30%, 50%, 70%, 90% and 100% ethanol bath for 3 hours for solvent exchange (similar to the procedure described in [12]-[13]).

2.2.2. Supercritical extraction of the gel-oil dispersion

The detailed description of the apparatus used is shown in fig. 2. In a typical experiment, 1400 ml of W/O emulsion were placed into the 4l cylindrical stainless steel vessel. Supercritical (SC) CO₂ was delivered using a high pressure diaphragm pump and was introduced from the top of the vessel at constant flow rate (200 – 300 g/min). Temperature was maintained constant (40°C) using oil heating jacket. At the outlet of the vessel SC-CO₂ loaded with solvent was directed to another 2l cylindrical stainless steel vessel (separator), where the liquid oil and solvent was separated. The pressure and temperature of the separator were maintained constant at 40°C and 60 bar respectively. Solvent-lean CO₂ was then recycled for the process. When the extraction was complete the aerogel microspheres were removed from the 4l autoclave and the solvent-oil from the bottom of the separator. Typically

the recycled CO₂ was exchanged by the fresh one at least four times during the extraction process to insure the complete drying of aerogel.

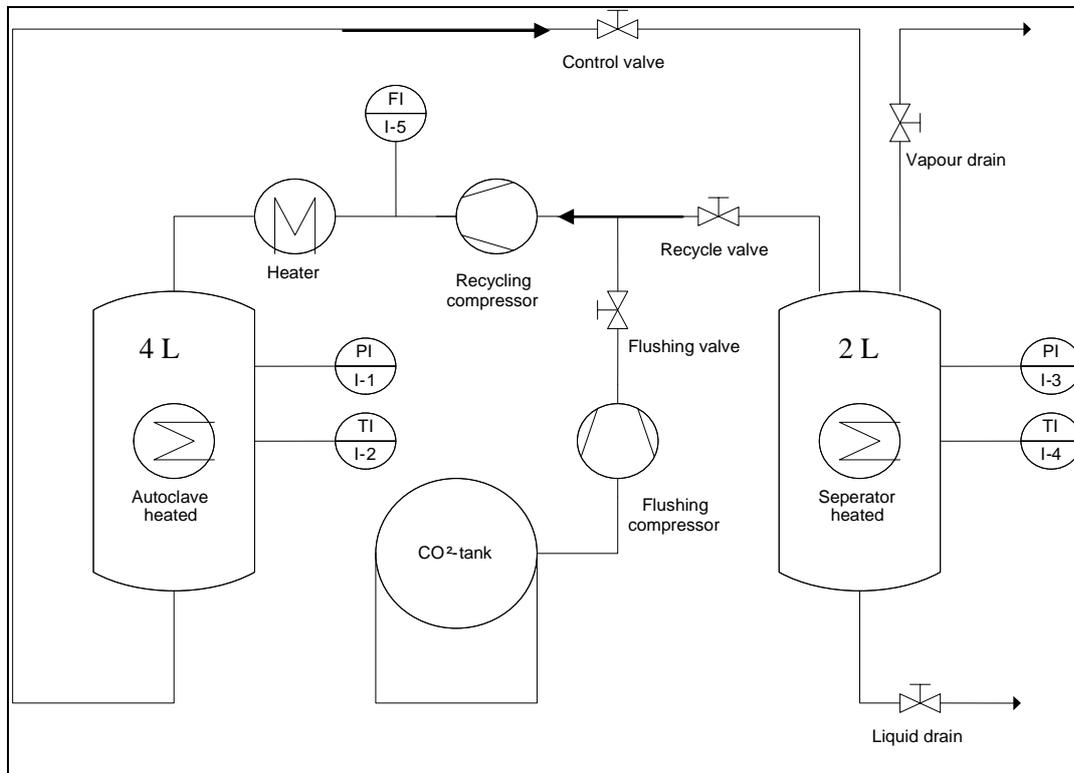


Fig. 2: schematic diagram of the 4L supercritical extraction unit.

2.3. Analysis

The produced microspheres were then characterized using different methods to evaluate the production process and the effect of process parameters. Surface area, pore size and pore size distribution were analyzed using nitrogen adsorption/desorption (surface analyzer Nova 3000e). Particles size distributions were measured using laser diffraction spectrometer (Sympatec Helos). Particles shape and form were analyzed using light microscopy (Zeiss Microscope Axio Scope) and scanning electron microscope (SEM) (Leo (Zeiss) 1530).

3. RESULTS AND DISCUSSION:

Particles shape and size distribution produced by the emulsion process depend on different factors. Obviously, the mixer shape and speed is the main parameter to control the dispersion of the aqueous phase in the continuous phase. Increasing the mixer speed result in stronger shear forces and turbulence, as a result the emulsion droplets will be smaller, and consequently the gel microspheres will have in general smaller mean size [14], [15]. However, this is not a straight forward relation, the reduction of droplet size with increasing mixer speed depends on many other parameters like the viscosity of the dispersed and the continuous phases, the interfacial tension between the two phases, their volume ratio, the size ratio of mixer to the mixing vessel, mixer(s) number and shape [1]. In this work two different

stirrer form at varying revolution speed were used. The effect of this and other production parameters on the properties of the resulting aerogels is discussed in details.

3.1. Silica aerogel microspheres

3.1.1. Particle shape and size distribution: effect of agitator shape

For the first set of experiments, four blades radial stirrer (diameter = 5 cm) were used to emulsify 200 ml sol-oil phases (1:1 volume ratio) in 600 ml vessel (9 cm internal diameter). The resulting aerogel particles were observed under light microscope. It has been noticed that for high stirring rate (1800 rpm) particles exhibit neither uniform shape nor spherical particles were obtained (fig. 3a). At lower stirring rate (800 rpm) microspherical particles were formed (fig. 3b).

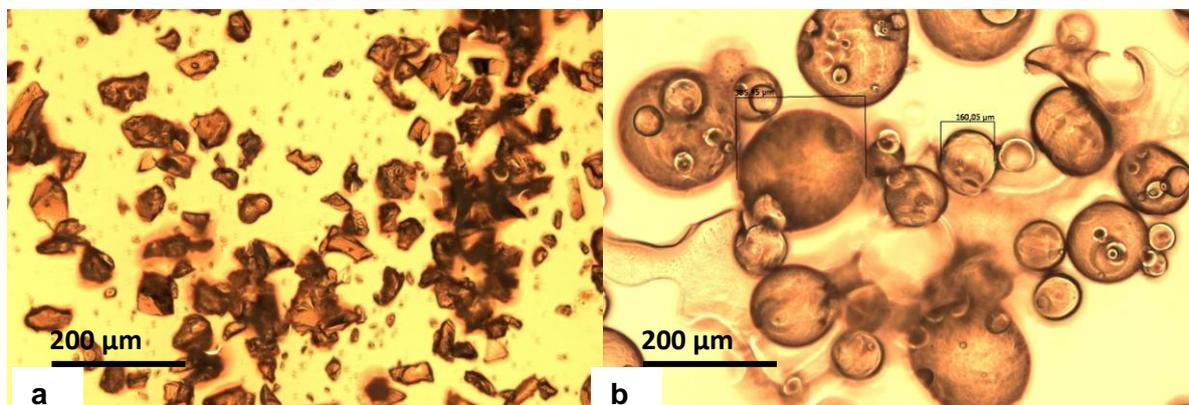


Fig. 3 effect of stirrer revolution on the form of aerogel particles: a) stirring speed = 1800 rpm; b) stirring speed = 800 rpm

Although spherical particles were obtained, for many applications it is beneficial to have smaller mean particles size as the one achieved at this conditions (less than 100 μm). However it is not possible using this stirrer type due to high shear rate applied to gel particles during mixing. Moreover, radial mixers result in such flow profile, that particles collide with the vessel walls. This amplifies high collision energy which leads to the abrasion and distraction of the spherical gel particles. For this reason another type of stirrer, which allow high energy input and smooth flow pattern, namely two blades axial stirrer was chosen. For this type of stirrer it was possible to produce spherical particles at much higher revolution speed (up to 2000 rpm). Based on this fundings all further experiments were conducting using this type of the stirrer.

3.1.2. Effect of stirring speed and other process parameter

In this set of experiments the two blades axial stirrer (diameter = 6 cm) were used to emulsify 200 ml of system (sol:oil phases volume ratio= 1:1) with different revolutions speed. Particle size distributions (PSD) as a function of the stirring speed determined by laser scattering analysis are reported in fig. 4 and table 1. The mean particle diameter (D_{50}) varies from 1730 μm to 143 μm , when the stirrer revolution varied from 200 to 1300 rpm respectively (table 1). These results confirm the well known statement that the main factor in controlling the PSD is the stirrer revolution [15].

Table 1: particle size distribution of the aerogel microspheres produced at different revolution speed. SD=standard deviation.

rpm	200	300	400	500	600	800	1300
average (μm)	1720	1615	996	908	601	332	155
SD (μm)	551	614	495	449	339	151	116
D ₁₀ (μm)	1166	987	19	495	281	194	46
D ₅₀ (μm)	1729	1645	40	842	566	310	143
D ₉₀ (μm)	2267	2214	57	1386	957	494	277

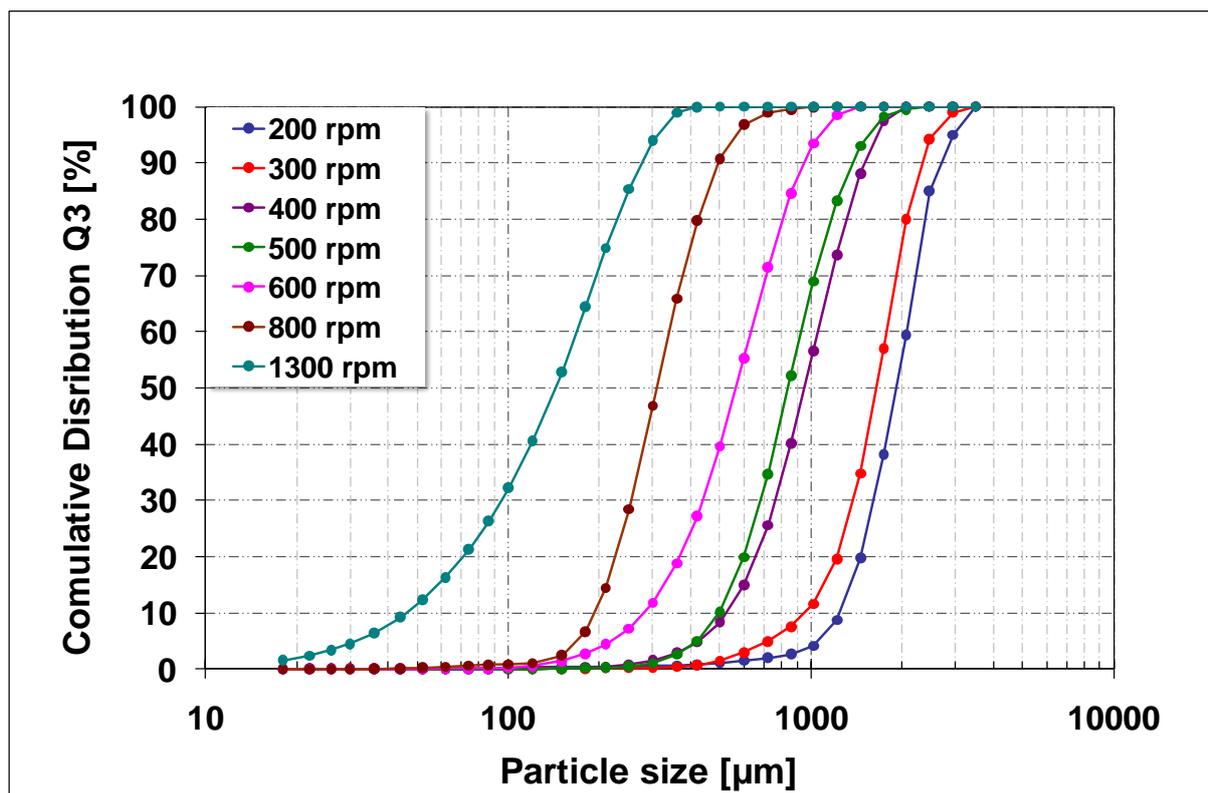


Fig. 4: cumulative particle size distribution as a function of revolution speed

Obviously, the PSD is relatively broad in all cases. Among many factors, affecting this property the viscosity of the dispersed as well as the continuous phase plays a major role in controlling PSD in the emulsion process [6],[16]. In our process the viscosity of the continuous phase remain nearly constant through the experiment, however, the viscosity of the dispersed phase (sol phase) increases continuously with time until the formation of the gel particles. This might lead to the widening of the resulting particle size distribution (table 1).

The impact of the volume ratio between the dispersion phase and the continuous phase on the PSD of the resulting microspheres is not fully understood. Various studies report reduction of the mean particles size with reducing the volume of the continuous phase [17], while in other studies no significant effect was observed [18]. In this study three different sol:oil volume ratio phase ratios were investigated, namely; 2:1, 1:2 and 1:1. For the largest sol:oil ratio (2:1) no microspheres could be formed. Microsphere formation at lower phase ratios (1:1 and 1:2) exhibits no significant difference. Based on these findings the sol:oil ratio of 1:1 was chosen for further experiments, since the minimum of oil phase is desired for the further extraction.

In future, surfactants or viscosity-enhancing stabilizer can be added to the continuous phase to produce smaller mean particles size and reduction of the PSD width.

Structural properties of silica aerogel microparticles

Figure 5 shows typical silica aerogel microspheres produced by the process discussed above. Obviously the particles have a spherical shape. For all samples, density, surface area, pore size and pore volume were measured. It has been observed that these properties do not depend on the specific parameter of the emulsion process, but rather on the sol-gel process itself (catalysts, component ratio etc.). Average values resulting from the multiple measurements are as follows: density= 0.15 ± 0.055 g/cm³, specific surface area = 1020 ± 90 m²/g, pore volume= 4.73 ± 1.17 cm³/g, and pore radius= 8.34 ± 1.66 nm.

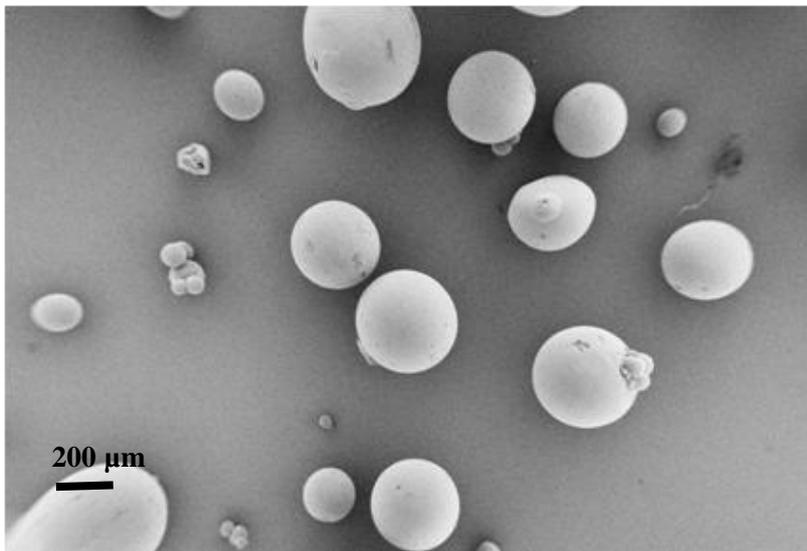


Fig. 5: SEM image of silica aerogel microspheres. Obtained conditions: (700 rpm, two blades axial stirrer (D: 6 cm), 1:1 phase ratio)

3.2. Alginate aerogel microparticles

Based on the experiences with the production of silica aerogel microparticles, the suggested process was extended to alginate systems.

Please explain here the main differences (solvent exchange).

In all cases four blades radial stirrer (diameter = 5 cm) were used to emulsify 100 ml aqueous phase in 200 ml oil in the 600 ml vessel (9 cm internal diameter). Following parameters were varied: viscosity of the water phase and stirring rate. Independent on the parameter combinations, for all experiments no spheres but rather irregular microparticles were produced (fig. 6).

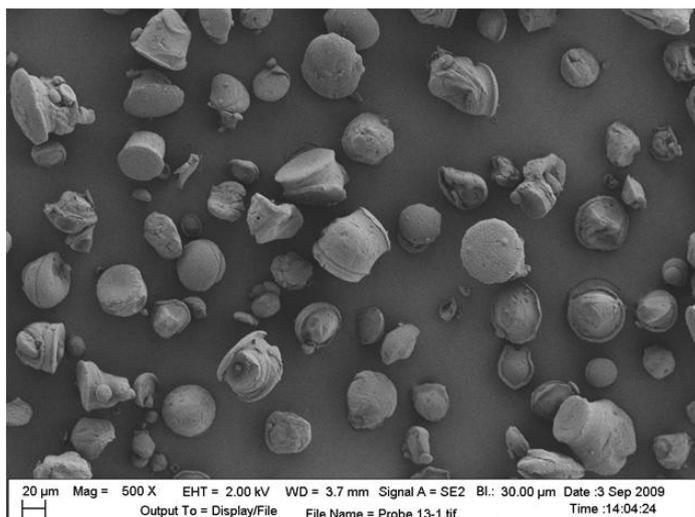


Fig. 6: SEM image of alginate Aerogel micro-particles obtained by 2000 rpm

This results most likely from the cross-linking process in the liquid droplets. In all experiments the diffusion setting method [??] was used. Here the divalent cations (Ca^{2+}) which catalyze the crosslinking are added to the emulsion and diffuse into the droplets of alginate solution (dispersed phase). Extremely rapid gelling kinetics is observed in this case, often causing the gel to be inhomogeneous, since the concentration of the cations decreases towards the middle of the gel [19]. This problem can be overcome by using the other cross-linking mechanism allowing slower gelation. Calcium carbonate (CaCO_3) can be used, since it shows a slow release of cations ions regulated by the change of pH or/and a limited solubility of the calcium salt source. A homogeneous distribution throughout the gel can be achieved with this preparation [20]. This strategy will be used in our future work.

Although no spherical form of the microparticles was achieved, they exhibit a sharper particle size distribution compare to that of silica aerogel microspheres (fig. 7). Moreover, the measured specific surface area ($391 \pm 11 \text{ m}^2/\text{g}$) was larger as any corresponding values for the alginate aerogels obtained with the same G/M ratio reported in the literature [21]-[24]. Obviously emulsion process enables the production of alginate aerogel microspheres which are highly relevant for the pharmaceutical industry [5]. However more investigations are required to understand the effect of production parameters on the properties of the final product.

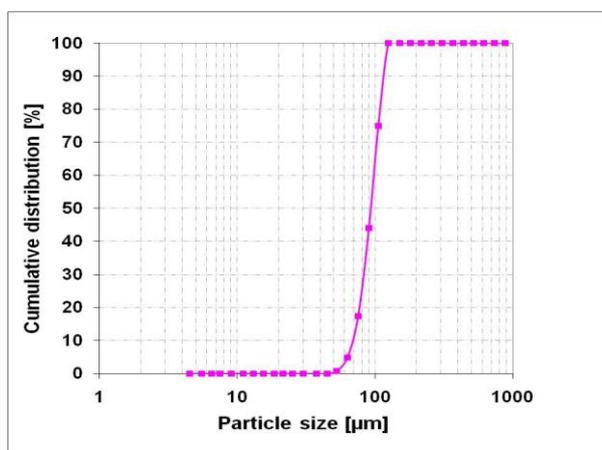


Fig. 7: cumulative particle size distribution for alginate aerogel micro-particles. Conditions: 4 blade radial stirrer (d: 5cm), 2000 rpm, 2:1 O/W phase ratio.

4. CONCLUSIONS

Supercritical extraction of emulsion is proposed as a versatile method for industrially relevant production of aerogel microspheres in a robust and reproducible manner. Two different types of aerogels, silica and alginate, were produced by this process. The influence of the process parameter (stirrer shape, stirring speed, phase volume ratio) on the properties of the produced particles was investigated. In case of silica aerogels, stirrer form and revolution rate is the main factor that controls the PSDs of the resulted microspheres. Depending on the conditions, silica aerogel microspheres with mean diameter from 155 μ m to 1,7 mm were produced. The internal structural properties of the aerogels (surface area, pore size) are less affected by the emulsion preparation, but rather by the composition of the sol itself and show similar values as the corresponding monolithic aerogels. Extension of the proposed technique to the alginate aerogels lead to non-spherical aerogel microparticles with sharp particle size distribution. Alginate aerogels produced by the supercritical extraction of emulsion have the largest specific surface area in comparison with literature values for corresponding alginate samples.

Principally, the process suggested in this work allows the large scale production of supercritically dried aerogel microspheres

5. References

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