Constant flux microfiltration with sieves with uniform pores

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Keywords: shear induced diffusion, microfiltration, Computational fluid dynamics, constant flux

Shear induced diffusion (SID) is a result of particles influencing the movement of other particles in flow. Large particles are more affected by this, and preferentially move to the centre of a channel. When using this principle in a closed channel prior to a microfiltration system that has uniform pores, filtration can be enhanced, and even pores bigger than the particles can be used for fractionation (figure 1). It was previously shown that the process can be operated at constant flux and has low energy and water demand.

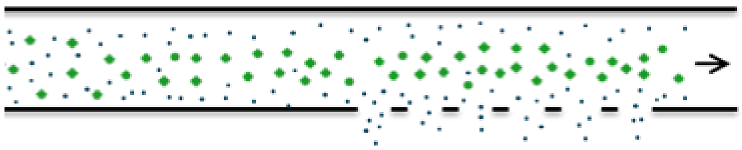

Figure 1. Schematic view on fractionation due to shear induced diffusion

In this NanoNextNL project the focus is on setting up a computational fluid dynamics (CFD) model to describe the phenomena of SID in a porous system, including the transmission / retention of particles for different membrane designs. The first results describe the separation mechanism and flow profile (see Figure 2 and 3) and are validated with literature and experimental data. The results show that there is a very good match between the experiments and the model, and that the particles are more concentrated in the centre of the channel. Next, membrane and process design will be considered to chart optimal separation conditions.

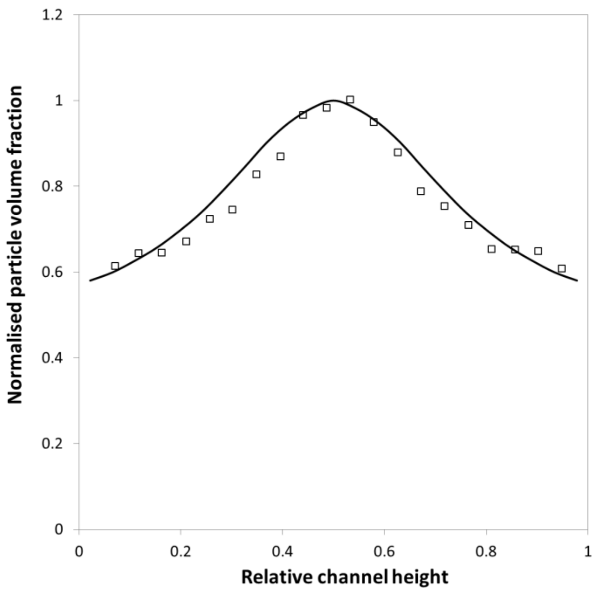

Figure 2. Normalised particle volume fraction (relative to the highest value) vs. the relative channel height, for $\phi_{bulk} = 0.5$. Experimental results by T.X. van de Laar (□); Our model results (line)

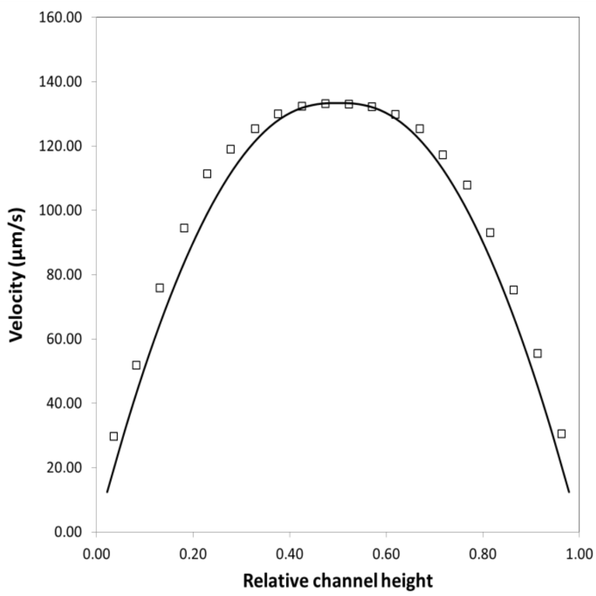

Figure 3. Velocity vs. the relative channel height, for $\phi_{bulk} = 0.3$. Experimental results by T.X. van de Laar (□); Our model results (line).

Introduction

As mentioned in the abstract, microfiltration can be facilitated based on natural migration behaviour of particles and/or droplets that are in the micrometre range. In that respect, the findings presented here are relevant for many processes in which these particles/droplets occur, e.g. emulsion production and separation processes (Schroën et al. 2016). The current paper, focusses on separation processes, and more specifically on filtration processes carried out with metal sieves with large pores that were first presented by van Dinther and co-workers (van Dinther et al. 2013). In the abstract on page 1, the theoretical background was touched upon and illustrated in the two figures on page 2; more information can be found in (Drijer et al. 2016). In the theory section of this extended abstract, rules of thumb are presented with which various transport mechanisms can be distinguished.

In order to make good use of the transport phenomena described here, a membrane or sieve with uniform pore size is needed (Van Dinther et al. 2011; Van Dinther et al. 2013). From literature, only limited examples are known such as Nuclepore membranes made by track etch technology (GE Whatman), and microsieves made through photolithographic technology (van Rijn & Elwenspoek 1995; Aquamarijn microfiltration BV). Besides, metallic sieves (e.g. Veco website) with very uniform pores made by electrochemical techniques have been used in earlier work done in our group. Images of all these membranes are shown in figure 4. Both microsieves, and metallic Veconic sieves can be designed with considerable degree of freedom in pore geometry, as illustrated in Figure 4 for the Veconic sieves.

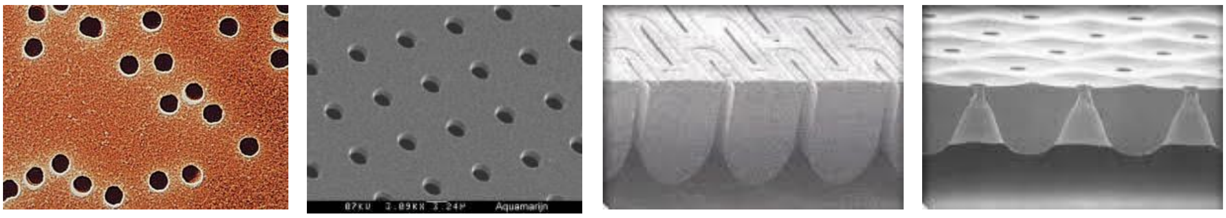

Figure 4. Examples of membranes, and sieves with uniform pore size. From left to right, Nuclepore membrane, Microsieve, Veconic metal sieve with slit-shaped pores, Veconic metal sieve with round pores. All images are taken from the internet.

In the work of Kuiper and co-workers (Kuiper et al. 2000) and Van Rijn (Van Rijn 2004) microsieves are described extensively including their use in beer filtration (Kuiper et al. 2002) albeit on relatively small scale. The fluxes are very high, and this calls for accurate control of the permeate flow to prevent/control accumulation, including the use of strategies often applied in microfiltration such as very frequent back pulsing and regular cleaning to keep the fluxes at an acceptable level (Rodgers & Sparks 1992).

When using any type of membrane, especially one with high flux and uniform pore size, better understanding of particle migration behaviour is expected to have an impact on how these processes may be run more efficiently, as has been demonstrated in the work of Van Dinther (van Dinther 2012). In the theory section we present the dimensionless numbers that can be used to distinguish between the various particle migration regimes. Most of these considerations revolve around a single particle size.

In the experimental work, we have taken this one step further by investigating separation of milk to which various amounts of cream were added (2.3, 4, 7.5%; typical droplet size 0.1 to 15 micrometre). We have done this for limited experimental conditions, but could show that also for this polydisperse feed solution, size separation is possible through the use of membranes with pores considerably larger than the particles that are being separated.

Theoretical framework

The particles present in cream can make use of different transport mechanisms that are summarised in Table 1. The last entry relates to fluid skimming, for which a dimensionless time is used that characterises the ratio of the time needed to flow into the pore $t_{\perp}$, and across the pore $t_{\parallel}$. If the first time exceeds the latter one, the particle is captured in the pore and dragged into the permeate (Van Dinther et al. 2011). The first three entries, shear-induced diffusion, inertial lift, and Brownian motion, can be characterised by Peclet and Reynolds numbers that are further defined underneath the table (Van Dinther, Schroen, et al. 2013; van der Sman 2009; Van Der Sman & Vollebregt 2012).

Table 1; Various particle transport mechanisms, the fluids in which they occur, and the typical size of the particles involved, and the dimensionless numbers that can be used to characterise a specific mechanism.

Mechanism	Type of fluid	Dimensionless numbers
Shear-induced diffusion	Concentrated solutions; 0.1<d<10 (μm)	Pe > 1, Re_p <1
Inertial lift	Diluted solutions; d>10μm	Re_p>1
Brownian motion	Any solution; d<0.1μm	Pe<1
Fluid skimming	Diluted solutions (<5%)	$\theta = \frac{t_\perp}{t_\parallel}$

With: Pe, the Peclet number defined for our system as:

$$Pe = \frac{\dot{\gamma} a^2}{D} = \frac{6\dot{\gamma} a^3 \bar{\eta} \pi}{kT}$$

And the particle Reynolds number, Re_p as:

$$Re_p = \frac{\dot{\gamma} a^2 \rho_f}{\eta_f}$$

In which, a, the particle size (m), $\dot{\gamma}$ the shear rate (1/s), D the Brownian diffusion coefficient,, η_f the fluid viscosity (without droplets Pa s), $\bar{\eta}$ the suspension viscosity (including droplets; Pa s), k the Boltzmann constant ($1.380 \cdot 10^{-23}$ J/K), T the temperature (K), and ρ_f the fluid density (kg/m^3).

In general, it is thought that small particles are subject to Brownian motion, large particles to inertial lift, and intermediate particles to shear-induced diffusion (depending on the concentration used). Fluid skimming is expected to be important for both intermediate and large particles, where the effect created needs to be weighed against that of the other mechanisms.

Experimental section

The membrane module had a channel height of 2 mm, was 40.5 cm long, and consisted of a closed channel followed by a round nickel sieve (1.39 cm^2) with uniform spherical pores of 20µm (Veconic sieve, Stork Veco BV, The Netherlands) placed at 34.5 cm. The closed channel allows a fully developed velocity profile and migratory effects to establish due to hydrodynamic inter-particle interaction (see also figure 1-3, please note that for the model results shown in figures 2 and 3 different channel dimensions were used).

Prior to separation, the system was cleaned with 2 L of water (45°C, v = 0.15 m/s), 1 L of T-Pol solution (0.2% vol/vol, v = 0.15 m/s), and 1 L of water (40°C, v = 0.15 m/s) respectively. The milk with various fat contents (2.3, 4, 7.5%) was first heated to 40 °C, and fed to the system with a positive displacement pump (VG1000digit, Verdergear, Germany). The feed solution was always 150 mL. A pressure sensor (EL-PRESS P-502C, Bronkhorst High-Tech B.V., the Netherlands) was installed at the beginning of the module, and the data were recorded with Bronkhorst High-Tech software. The cross-flow velocity was kept constant at 0.78 m/s, and the permeate flux was varied from $4 \cdot 10^{-5}$ to $3 \cdot 10^{-4}$ $m^3/m^2/s$ (corresponding to 100 – 1000 $l/m^2/h$). The permeate was measured with a balance (CP4202S, Sartorius, Germany). The set-up was run until 1.5 ml of permeate was obtained, and the size distribution of the cream was measured both in the permeate and in the retentate with a Mastersizer 2000 (Malvern Instruments Ltd., UK).

Results

A typical result obtained in the filtration experiments is shown in Figure 5, in which the fat droplet size distribution is given for the permeate (green line) and the retentate (blue line) that coincides with the feed solution (red line). The amount of liquid taken from this experiment is in general low compared to the total volume that was used and that explains why the retentate and feed solution have the same fat droplet size distribution. This is in contrast to the permeate in which much smaller fat droplets are present. Clearly, the large particles are no longer present in the permeate, and there are more small ones than present in the feed solution.

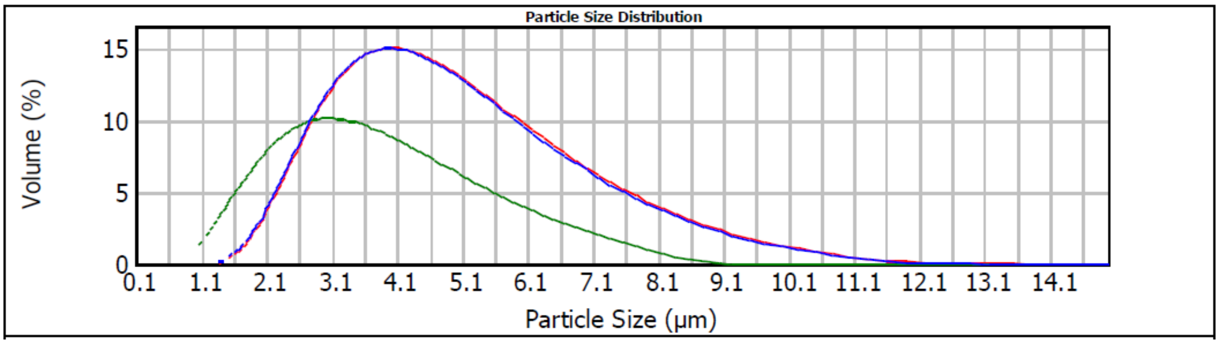

Figure 5. Droplet size distribution of permeate and retentate in a typical filtration experiment carried out with 4.1% fat in the feed solution (full milk).

The results shown in Figure 5 can be caused by various particle transport mechanisms as explained previously; fluid skimming and shear-induced diffusion being the most likely causes due to the size of the droplets, and the concentration that is used (which is expected to be on the low side for SID based on the dimensionless number analysis; see table 1). In order to check this, various experiments needed to be compared, which was not trivial, since the size distribution of the fat droplets differ on a day to day basis and among individual animals. At the highest milk fat concentration used (7.5), we saw that the differences in size (here expressed as a $d(0.9)$, the 90% point of the fat droplet size distribution) between permeate and retentate were very small, while at a fat content of 2.3 and 4%, considerable differences were noted (see Figure 6 for milk with 4% fat content).

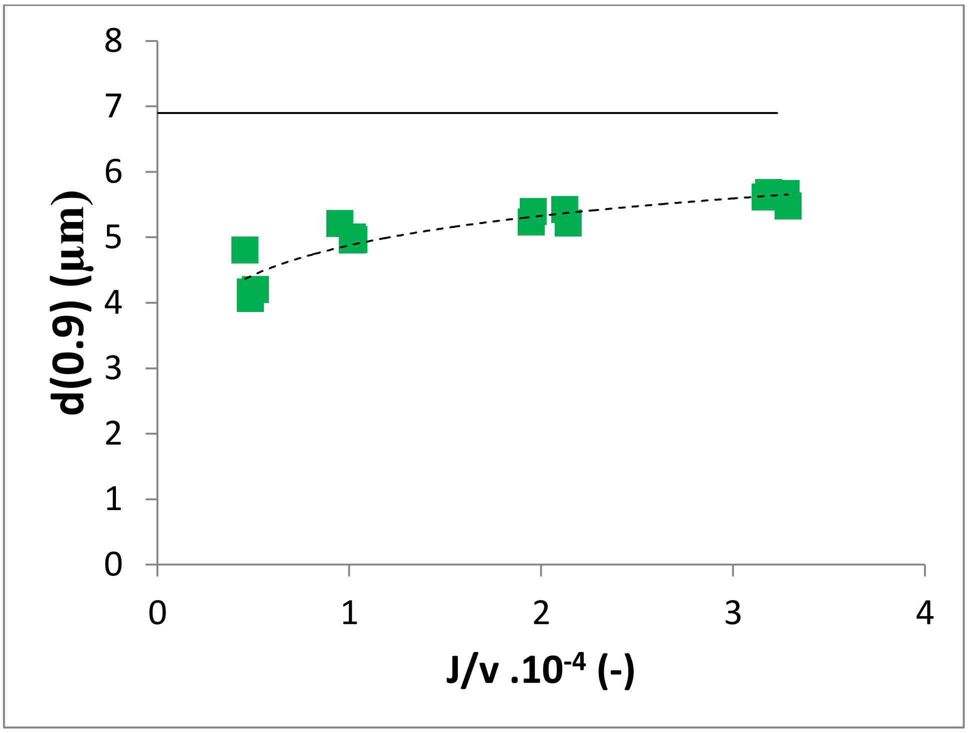

Figure 6. The fat droplet size in the permeate as function of the dimensionless time, here calculated as the flux divided by the cross-flow velocity. The horizontal line indicates the average size of the particles in the feed in terms of *d*(0.9) the 90% point of the size distribution.

The average size of the fat droplet used for the experiments shown in Figure 6 was just under 7 micrometre, as is indicated by the horizontal line. The size of the fat droplets in the permeate are considerably smaller, and this effect is greater for lower fluxes corresponding to low *J*/*v* values, since the cross-flow velocity was kept constant. When comparing with results obtained at low fat concentration, the same trend was seen, and this is in line with the findings of van Dinther (Van Dinther et al. 2011), who noted that at concentrations below 5% e.g. yeast cells in the permeate were considerably smaller than in the feed. As was the case in that work, the graphs could be compiled into one master curve, based on the actual size of the particles, and these findings make it highly likely that the underlying mechanism was fluid skimming, since that acts at low concentration and is a strong function of the size of the droplets. At concentrations of 7.5 and 10% this mechanism was lost, most probably because the particles present in the feed prevented the skimming particles from returning into the feed solution. Shear induced diffusion will have taken place but the fluxes were too high to notice any difference in size.

Interestingly, the large particles in the feed solution were never seen in the permeate. We tested whether this could have been due to fat droplet break-up due to shear forces in the set-up, but that turned out not to be the case. The effects that were noted are clearly due to particle transfer that allowed us to continuously operate the set-up (at high flux: 100-1000 $l/m^2/h$), without the need for back pulsing etc. As a matter of fact, back-pulsing would have destroyed the beneficial effect that was created by using laminar flow conditions, that are also much less energy intensive as standardly used in filtration processes.

Conclusions

Using particle transport phenomena to design filtration processes is a novel approach that may lead to new technology that is inherently less energy consuming. However, to reach this, thorough understanding of the underlying mechanisms is needed.

In this paper we showed in the submitted abstract section, that it is possible to describe particle transport in great detail using accessible software. The simulations showed that the particles have the tendency to migrate toward the middle of a channel, therewith facilitating filtration.

In the experimental section in the main text, in which filtration was investigated, we showed that the underlying mechanisms also hold for very poly-disperse milk with droplet sizes ranging from 0.1 to 15 micrometre. The permeate contained considerably smaller fat droplets than the feed, as a result of fluid skimming effects.

Both shear-induced diffusion and fluid skimming have a positive effect on separation behaviour, since particles move ‘out of the way’ when the process conditions (ratio of pressure and transmembrane flux, and pore geometry / uniformity) are chosen such that these effects are allowed to take place. We believe that designing filtration-based separation technology using particle transport phenomena as a starting point can lead to a new generation of separation devices that are intrinsically more sustainable.

Acknowledgement

This work is supported by NanoNextNL, a micro and nanotechnology consortium of the Government of the Netherlands and 130 partners.

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