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Separation process for very concentrated emulsions and suspensions in the food industry

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ABSTRACT

Separation of concentrated food suspensions and emulsions by e.g. microfiltration is currently not possible and therefore preceded by dilution, wasting energy and water. A new approach is shown, with sieves having pores much larger than the micron-sized droplets, low cross-flow velocities and a non-porous channel before the sieve. The complex behavior of concentrated emulsions under laminar flow in a non-porous channel causes depletion of large droplets and higher concentrations of small droplets near the wall. When the liquid flow through the pores relative to the channel flow is below a certain value, the liquid from the pores is completely devoid of larger droplets and has higher concentrations of small droplets than in the channel. This effect was caused by a combination of shear-induced migration in the channel and the interaction of droplets with the pores. Industrial separation processes can operate at high concentrations under mild conditions, potentially saving water and energy.

Industrial relevance: Separation of suspensions, essential in processing any harvested agricultural material, is usually done by membrane separation or centrifugation, which is based on size exclusion by a membrane or a difference in density between particles and fluid, and this places intrinsic boundaries on the concentrations that can be processed, typically <5%. The sieve filtration process for micron-sized particles introduced here operates best at very high volume fractions and much lower cross-flow velocities than currently used. Industrial application of our finding could therefore have major benefits: no water is needed for dilution and waste is minimized. Besides energy used for dehydration and the separation process is reduced.

1. Introduction

Separation of suspensions, essential in processing any harvested agricultural material, is usually done by membrane separation or centrifugation. The separation principle is based on size exclusion by a membrane or a difference in density between particles and fluid, and this places intrinsic boundaries on the concentrations that can be processed, typically <5%. Dilution is applied to reduce the detrimental effects of accumulation and clogging of particles, which is especially an issue in membrane separation (Chavan, 1983; Goldsztein, 2005; Leniger & Beverloo, 1975; Lisińska & Leszczyński, 1989). If separation at volume fractions above 20% were possible this would dramatically decrease water and energy usage in the food industry.

The processing of starch is such an example. Corn wet milling is the most energy intensive industry within the food industry (Galitsky et al., 2003). Starch separation and purification is mainly carried out with centrifuges or hydrocyclones, where large amounts of water are used for the final purification step. As a result, often large amounts of starch are present in wastewaters from starch industry and this is a substantial problem from an economic and environmental aspect (Blanchard, 1992).

In this article a promising new route for the separation of concentrated food suspensions and emulsions with fine sieves is shown. The sieves have pores much larger than the micron-sized droplets and are therefore not called membranes, which is usually the case in membrane microfiltration. To highlight this, also the pressure over the sieve is called trans-sieve pressure in the article. Besides, the cross-flow velocities used are much lower than in current microfiltration processes and additionally a non-porous channel is installed before the sieve. The separation principle is based on the complex behavior of concentrated emulsions under laminar flow in a non-porous channel (called shear-induced diffusion) and the interaction of droplets with the pore of the fine sieve. The principles will be explained below.

1.1. Theoretical background

At high concentrations, suspensions tend to exhibit complex segregation. Hydrodynamic diffusion is the hydrodynamic interaction of more than two suspension particles, resulting in a random

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displacement of the particles from their original flow lines (Breedveld, van den Ende, Jongschaap, & Mellema, 2001). These interactions are much more abundant at higher concentrations, so significant hydrodynamic migration takes place especially in concentrated suspensions. Particles generally move towards regions of lower shear rate. This was investigated for Couette flow (Abbott et al., 1991; Graham, Altobelli, Fukushima, Mondy, & Stephens, 1991), pipe flow (McCarthy & Kerr, 1998) and described in modeling studies (Nott & Brady, 1994; Phillips, Armstrong, Brown, Graham, & Abbott, 1992; Vollebregt, van der Sman, & Boom, 2010). This migration has a lot of influence on the viscous behavior of suspensions and emulsions, important in a lot of natural and industrial processes (Cheng, McCoy, Israelachvili, & Cohen, 2011; Chow, Sinton, Iwamiya, & Stephens, 1994). Besides, hydrodynamic interactions can lead to either reversible or irreversible motion, depending on the amount of deformation that is imposed on the suspension (Pine, Gollub, Brady, & Leshansky, 2005). Most important in relation to this study is that several authors showed that in bidisperse suspensions, larger and smaller particles tend to segregate (Husband, Mondy, Ganani, & Graham, 1994; Krishnan, Beimfohr, & Leighton, 1996; Lyon & Leal, 1998; Semwogerere & Weeks, 2008; Shauly, Wachs, & Nir, 1998).

Hydrodynamic interaction can be divided into interaction between different particles in the fluid itself (a volume effect), and interaction between particles and the wall (a surface effect).

1.1.1. Hydrodynamic inter-particle interaction

Phillips et al. (1992) proposed that hydrodynamic migration between particles in the bulk of the suspension is driven by gradients in particle volume fraction, in shear rate and in viscosity (Phillips et al., 1992). In Eq. (1) the relation between those factors is described in the shear-induced migration flux.

$$J_{mig} = -D_{shear}\nabla \ln\left(\dot{\gamma}\phi\eta^{\lambda}\right). \quad (1)$$

In which J_{mig} is the shear-induced migration flux (m/s), D_{shear} the shear-induced diffusion coefficient (m^2/s), $\dot{\gamma}$ is the shear rate (s^{-1}), ϕ the oil volume fraction (−), η the viscosity (Pa·s) and λ a constant (−). Since in Poiseuille flow the shear rate in the center of the channel is zero and highest at the wall of the channel, one can immediately see that migration of particles takes place from the wall, towards the center of the channel. D_{shear} is given by Eq. (2):

$$D_{shear} = K\dot{\gamma}a^2\phi^2. \quad (2)$$

With a the particle radius (m) and

$$K = 1 + 0.5e^{8.8\phi}. \quad (3)$$

The average shear rate ($\dot{\gamma}$) and the shear rate in Poiseuille flow very close to the wall ($\dot{\gamma}_{wall}$) are described in Eqs. (4) and (5) respectively.

$$\dot{\gamma} = \frac{6\overline{v}}{h} - \frac{12\overline{v}z}{h^2} \quad (4)$$

$$\dot{\gamma}_{wall} = \frac{8\overline{v}}{h}. \quad (5)$$

With $\overline{v}$ the average velocity in the channel (m/s), z the distance from the channel wall (m) and h the channel height (m).

Eq. (1) shows that particles are able to migrate to the middle of the channel against a concentration gradient and as a result in steady state the particles are concentrated at the center of the channel. The concentration profile in the channel depends on the degree of migration (related to the parameters mentioned in Eq. (1)) and the time the particle can migrate, being related to the non-porous channel length. Section 3.1 shows a theoretical example.

1.1.2. Hydrodynamic interaction between particles and the pore

While the hydrodynamic migration described before acts between particles in the suspension and thus is a bulk effect, there is an additional effect due to hydrodynamic interaction between particles and the pores of the sieve. As long as the longitudinal cross-flow dragging the particle over a pore mouth is large enough relative to the flow towards the pore, it will be taken up again by the feed, and will not enter the pore (Yan, Acrivos, & Weinbaum, 1991a, 1991b). Whether the flow pattern above a pore repeats itself over each of the subsequent pores depends on several factors. The trans-sieve pressure over the length of the sieve should be stable (~1% deviation), the dimensions of the pores should be equal and the flux should be low compared to the main flow (~0.5%) (Kim & Zydney, 2006). The result section shows the presence of both inter-particle interaction and particle pore interaction effects in a separation process.

Current membrane separation processes suffer from strong accumulation of components near and on the membrane and in the membrane pores (Belfort, Davis, & Zydney, 1994; Knutsen & Davis, 2006; Song, 1998; Wang & Song, 1999). Reduction of the accumulation through adjustment of the process conditions or by chemical modification of the membrane is complex and far from sufficient (Field, Wu, Howell, & Gupta, 1995; Howell, 1995; Saboya & Maubois, 2000; Sandblom, 1978; Tardieu, Grasmick, Geaugey, & Manem, 1998). In the experiments shown here a channel with two sections is applied: the first section has a non-porous wall, allowing hydrodynamic inter-particle interaction to take place in the channel, followed by a section with sieve where hydrodynamic interaction between droplets and pores occurs. The outer layers of the fluid are removed through the pores in the sieve.

The transmission (Eq. (6)) of particles of a specific size is defined with

$$Transmission = \frac{\phi_{p,i}}{\phi_{b,i}} \quad (6)$$

in which $\phi_{p,i}$ is the volume fraction of particle i in the fluid passing the pores (−) and $\phi_{b,i}$ is the average volume fraction of the same particles in the fluid inside the channel (−).

The effects of the hydrodynamic interactions between particles and particle and pore were assessed with concentrated emulsions, with different droplet sizes and using sieves with different pore geometries.

2. Materials and methods

Emulsions of silicone oil (density of 1.01 g/cm^3; silicone oil AR 20, Sigma Aldrich, Germany) in water were prepared at oil volume fractions ranging from 0.10 to 0.47. Depending on the oil volume fraction of silicone oil, demineralized water and span80 (Sigma-Aldrich, Germany) as well as Tween80 (Sigma-Aldrich, USA) were mixed in different ratios. The Span80 concentration was always 1% (w/w) as was the Tween80 concentration. A pressure vessel was filled with the mixture, which was then pressed six times through a 5 μm filter (PVDF Durapore, Millipore Corporation, Bedford USA) at 0.5 bar, which resulted in a droplet size of 5.5 μm (emulsion 1, span was 0.30). This emulsion was further refined by pressing it six times through a 2.7 μm filter under 2 bars (Glass microfiber GD/X, Whatman, GE, USA). The typical size of this emulsion was 2.0 μm (emulsion 2, span was 0.66); for the separation experiments emulsions 1 and 2 were mixed at set ratios. It was tested whether the emulsion could be made reproducibly, and this was the case. Further, it was checked whether the emulsions were prone to changes in droplet size during the experiments, and this was not the case. The emulsions are a reliable measuring system.

Filtration experiments were performed with the two emulsions that were mixed in a pre-determined ratio (20 vol.% large droplets