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On the bubble-surfactant interaction

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ABSTRACT

Surfactants play an important role in numerous chemical applications. Their effects on dispersion systems, as emulsions and colloids, are vastly studied. Yet, the dissolution (kinetics) of surfactants themselves has not received much scientific attention, despite the high implications for industrial applications. Nevertheless one can acknowledge the rapid growth of new technologies which are being considered to enhance various chemical processes, one being cavitation–the rapid growth and collapse of vapor bubbles, which results in the formation of shockwaves, streaming, free radicals, high local temperatures etc.

In this paper, we investigate the influence of cavitation on the dissolution rate of Sodium Dodecyl Benzene Sulfonate. Using a high-speed camera, we determined the physics of the dissolution process. We have shown that the presence of cavitation greatly enhances the dissolution rate of surfactant in water through a process comparable to cavitation erosion.

Finally, based on our findings, we also present the newly developed cavitation reactor, which could be potentially used for enhancing the process of washing powder dissolution in home appliances.

1. Introduction

Surface active agents, or surfactants as they are named in short, are among the most versatile materials in chemical and process industry [1]. Its amphiphilic nature, containing both hydrophilic and lipophilic functional groups in one molecule, exhibit fascinating interfacial behaviour. Their use is crucial for countless applications and processes, ranging from pharmaceuticals, petroleum industry, mining and metal industry, paints, cosmetics, cleaning, etc. [2].

Additionally, surfactants are indispensable in the laundry process. They are essential for soil detachment from textile as well as for stabilizing washing solution (entrapping soil) and therefore preventing redeposition of soil back on fabric [3]. For this reason, surfactant concentration in laundry detergent formulations is in the range 10–40% [4].

While the mechanism of textile washing, depending on the type of soil, type of textile fibre and detergent composition is well understood [1–5], the preparation of the detergent has received only a little attention or researchers. This can lead to over- or under-estimation of appropriate washing time. Too short time can decrease the laundry efficiency and detergent residuals can remain on the textile even after washing. Too long dissolution time consequently leads to too high energy consumption. Considering that laundry machines are globally among the most common household devices, the economic and environmental "cost" of such misjudgement is high!

One of the current attractive ideas for optimization of dissolution process is its acceleration by cavitation–a process of bubble formation due to local depressurization. The process is similar to boiling but much more rapid and aggressive. It can be achieved by introduction of acoustic waves–ultrasonic cavitation or by increasing the velocity of the liquid flow–hydrodynamic cavitation. The basic physics of both are the same on a small scale, but the latter can be more efficiently exploited, mainly due to its continuous nature. At the end of the process, when the bubble enters a higher-pressure region, it violently collapses, causing damage to the solid surfaces, noise, local increase of temperature, shock waves, micro-jets, vibration and even radical formation and pyrolysis. Although the process is mainly considered as unwanted it can be applied to enhance the performance of many processes, provided it is well understood and controlled [6].

Most of the scientific research of cavitation in the field of dispersion systems is done on micro-mixing [7,8], emulsification and homogenization [9–12]. Cavitation is shown as a very desirable effect on those processes. High shear stresses, elevated turbulence level and microstreaming enhance mass transfer and disrupt the particles or droplets. The mean particle size is the most important parameter to evaluate dispersion quality in those studies. The common conclusion is, that with the application of ultrasound, the size of emulsions/particles is much smaller than with mechanical agitation under the same conditions [13–15]. Dissolution kinetics–our core interest, however, is not in focus of papers listed in this paragraph.

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In the paper, we investigate how bubbles interact with the surfactant grain by exposing it to ultrasonic cavitation. By observing the process with a high-speed camera, we were able to determine the physics of the solution process. Additionally, we show efforts to integrate the gained knowledge into a cavitation reactor where cavitation is achieved by hydrodynamics. The device could be installed into a washing machine to increase its washing and consequently also electrical efficiency.

2. Experimental work

Both, the bubble-surfactant interaction experiments and preliminary tests in cavitation generator were set-up at the facility for studying the exploitation of cavitation at the Faculty of Mechanical Engineering, University of Ljubljana.

2.1. The bubble–surfactant interaction set–up

The most common and reliable approach to study the cavitation process is by visualization, hence a transparent ultrasonic bath was machined. The bottom and the three sides are made of acrylic glass. The last, fourth side is made of stainless steel (Fig. 1). The micrometric movement of stainless steel side is excited by a piezoelectric transducer, emitting ultrasound at 33 kHz. This frequency has been selected based on the fact, that at 33 kHz ultrasonic devices exhibit the most aggressive cavitation [16]. The ultrasonic frequency is carried by a low frequency of 100 Hz, hence it is expected for the bubbles to appear periodically, every 0.01 s. We used the calorimetric method to determine the power of emitted ultrasonic waves [17]. Nominal (full) power of the bath is 45 W and the total volume of the bath is 1.1 L.

Sodium dodecyl benzene sulfonate (SDBS) purchased at Sigma-Aldrich was selected as investigated surfactant. SDBS is the most common surfactant used in laundry detergents [3]. 20 mg ± 5 mg SDBS samples were weighed using a precision scale. To affix the samples to the needle tip, the SDBS sample was hydrated and let to dry in ambient air for 24 h. Afterward, the samples and the needle tip were pressed together between two glass surfaces. This fixed the sample and shaped it in a disc, with the same thickness as the needle −2 mm and diameter of 5 mm (± 10%). The disc shape of the surfactant enabled to use the assumption, that the disc face area corresponds to surfactant volume.

Prepared samples were immersed in the center of the ultrasonic bath. The dissolution process was observed by the high-speed camera from the introduction of ultrasound, up to a point when the sample fully dissolved. Dissolution was evaluated for acoustic powers 45 W and 25 W, corresponding to full-power and approximately half-power of our ultrasonic device. The power of the device does not change the frequency or the size of the bubbles, just their number. In addition, experiments without cavitation were carried out as a reference. Instead of ultrasonic agitation, the bath was placed on a magnetic stirrer (IKA Labortechnik RCT basic) during these tests. The magnetic stirrer was set to 200 rpm, which was the maximal value, at which the air funnel did reach the sample.

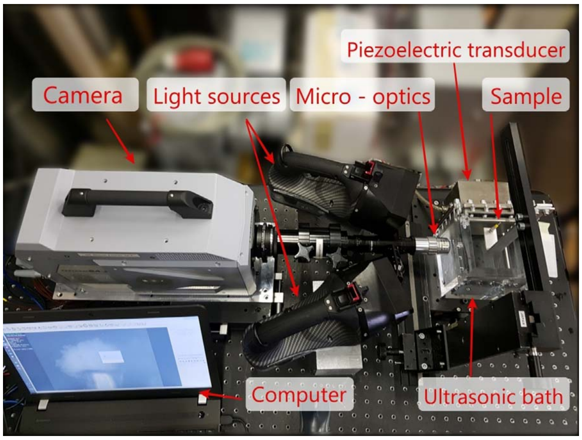

Fig. 1. Experimental set-up.

6 experiment repetitions were performed for each of the operating points (45 W acoustic power, 25 W acoustic power and silent runs). All experiments were performed at temperature 22 ± 0.5 °C. A typical experiment lasted about 15 s. In that time the temperature change was negligible and no cooling of the bath was required.

2.1.1. Observation techniques

The imaging system consisted of camera Fotron FastCam SA-Z, coupled with Mitutoyo M Plan Apo 5 x micro-optics or Nikkor 105 mm F 2.8 macro lens (depending on the region of interest). The illumination was provided by two 50.000 lm LED light sources. When observing cavitation, two different illumination arrangements are commonly used. One option is that the cavitation bubbles scatter the light (both the light source and the camera face the same direction as in Fig. 1). Images recorded this way have bright bubbles on a dark background. The second option is that observed bubbles are between the camera and the light source (camera faces the lights). With this arrangement, cavitation bubbles appear dark, while the background is bright. We have run experiments in both arrangements. It turned out that images recorded with dark bubbles proved somewhat easier post-processing for dissolution rate determination, while bright bubble images provided more qualitative information on the interaction with the surfactant grain. Images were recorded at 1000 frames per second for dissolution rate analysis and at 5000 frames per second for bubble-surfactant interaction observation. The image resolution was 640 × 512 pixels in both cases, what corresponded to spatial resolution of 10 to 20 μm per pixel, depending on the optics that was used.

2.2. Preliminary tests in cavitation generator

Moreover, we show a possible application of the discussed technique–to use cavitation for intensification of laundry aqueous detergent solution preparation. The experiment was designed to simulate an actual washing machine. Here the experiment and the results are given only in a brief form–a more thorough description of the work can be found in [18].

2.2.1. Set–up

A special rotary hydrodynamic cavitation generator (RHCG) was designed. The detergent dissolution rates were experimentally evaluated, for both cavitation and pure liquid flow regime, on a model washing machine. In addition, tests with a magnetic stirrer were performed as a reference.

The experimental set-up is presented in Fig. 2. Together with the rotary hydrodynamic cavitation generator, the experimental set-up consisted of a closed pressure tank, connection pipes and pressure (ABB 266 ABB 266 ast), flow (Bio-Tech: FCH-C-Ms-N) and temperature sensors (Fluke 51 II). Ports visible in Fig. 2 on the top of pressure vessel are used to fill the set-up with water and detergent. When operating, the mixture exits the vessel at the bottom, then it is led through RHCG, where it is exposed to cavitation. RHCG also serves as a pump. Water and detergent then flow through the control valve and back to the pressure vessel. The RHCG was driven with a single-phase electromotor, which is already present in most of the washing machines.

The design of the rotary hydrodynamic cavitation generator (Fig. 2, right) follows the basic principles of high shear mixing devices [19], adjusted so that it also generates cavitation. The RHCG is an assembly of rotor and stator discs with special geometry inside the closed chamber. Both the rotor and the stator have diameter 50 mm. They have 12 radial indentations, 3 mm deep and 4 mm wide. A more