Cavitation Inception by Almost Spherical Solid Particles in Water

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Abstract
The tensile strength of water increases when solid particles are filtered out, and it becomes greater the smaller the remaining particles are. Natural particles are of random shape, making parametric studies on the relationship between tensile strength and particle characteristics difficult. In this investigation, using degased tap water from which natural particles larger than about 1 (m were filtered out, the tensile strength was measured before and after seeding with almost spherical solid balls of diameters from 3 (m up to 76 (m. The smallest balls, though hydrophobic and notably larger than the remaining natural nuclei, had no measurable influence on the tensile strength. Seeding with balls at least a factor of ten to forty larger than the largest remaining natural nuclei reduced the tensile strength by only between 1/3 and 2/3 of that measured for the unseeded filtered water. On this basis it is concluded that a greater tensile strength is connected to the almost spherical solid balls than that connected to natural particles of the same size. The critical cavities developed from the larger balls had radii much smaller than those of the balls themselves. This supports the hypothesis that the cavitation nuclei are related to the fine scale surface structures observed on the balls. A model of their development is presented.

1. Introduction

The nature of cavitation nuclei has been a subject of continuous discussion in the cavitation community. Gas bubbles embedded in the bulk of a liquid are the first obvious candidate, but they dissolve (Epstein & Plesset, 1950) or disappear due to buoyancy unless they are somehow stabilized. Harvey et.al. (1944) proposed that gas nuclei are stabilized in hydrophobic conical cracks and crevices of solid surfaces. Though real surfaces generally do not exhibit such features, their model explains several experimental observations of cavitation inception. Greenspan & Tschiegg (1967) showed that the removal of particles larger than 0.2 (m diameter from water raised its tensile strength to about 200 bar. This supports the supposition that the free stream nuclei causing cavitation are closely connected to the solid particles always abundantly present in plain water. Recently it was suggested in a revised Harvey-type model (Mørch, 2000) that liquids may detach from solid surfaces at localities of concave curvature so that interfacial voids are formed. This is ascribed to interfacial liquid tension and to diffusion of gas molecules into the structured interfacial liquid. The voids may grow into stabilized cavitation nuclei if the sound field in the liquid sets up a broad-band resonance of the gas-liquid interfaces. In such cases a rectified diffusion of gas into the voids balances the diffusion out of them due to the excess pressure associated with their convex gas-liquid interfaces. Of course the degree of gas saturation in the liquid at the prevailing pressure also strongly influences this diffusion balance.

Natural nuclei are generally highly irregular and their surfaces exhibit a broad spectrum of local radii of curvature (apparent from Figure 1 in Crum (1980)). Attached gaseous voids are expected to develop at these irregularities, and their growth beyond critical size at exposure to tensile stress determines the tensile strength Pts of the liquid. In order to study how the tensile strength is dependent on the particles it is advantageous to replace the natural particles with well known ones. In this paper experiments with mono-sized almost spherical particles of different diameters and wetabilities are described.

2. Spherical solid particles

The tensile strength of a liquid increases if solid particles are removed by filtering - the more the smaller the remaining particles are. If the liquid is subsequently seeded with perfectly spherical particles of radius R which are totally hydrophobic[1] the theoretically smallest possible tensile strength $(P_{ts})_{R,\text{th}}$ is determined from the stress $p_\infty = p_{\infty,crit}$ that overcomes the surface tension force and makes a vapour cavity of initial radius R detach and grow, i.e.

$$(P_{ts})_{R,\text{th}} = 2\gamma /R = - (p_\infty - p_v)_{\text{crit}}. \qquad (1)$$

[1] Actually, this is not possible due to van der Waal's forces. A 100% hydrophobic sphere equals a vapour bubble.

in which γ is the surface tension constant and p_v is the vapour pressure. Thus, a totally hydrophobic spherical particle R = 1.5 μm in water results in $(P_{ts})_{R,\text{th}} \approx 100$ kPa. In cases of partially hydrophobic spheres the tensile strength is greater because liquid-solid bonds have to be broken. Hydrophilic, *perfect* spheres are not responsible for the tensile strength because the molecules of the liquid bond better to the sphere than to neighbouring liquid molecules. However, real particles of spherical shape exhibit small-scale deviations from sphericity, so that locally concave surface structures are formed. At such localities interfacial gaseous voids - cavitation nuclei - much smaller than the particles themselves may be in dynamic equilibrium (Mørch, 2000). By pressure reduction these voids grow, and adjacent ones may merge into larger ones. In a fast pressure reduction the content of non-condensable gas remains that initially present in the voids which expand into essentially vaporous cavities. The void that first reaches hemispherical form determines the critical pressure due to the globally spherical particle.

In the present experiments where filtered water was seeded with almost spherical solid balls, Dynospheres, four of the batches were characterized by the manufacturer (Dyno Particles AS, Norway) as hydrophobic and one batch as hydrophilic. Their density was about $1.05 \cdot 10^3$ kg/m^3. Table I presents the manufacturers particle characterization as well as our size measurements. Figures 1-5 show scanning electron microscopic (SEM) pictures of the balls used for seeding. We notice that within each batch the balls are remarkably uniform, and they are very close to being spherical, except the 3 μm balls in Figure 2, which are deformed to some extent and exhibit "mountains" of dimensions up to 300 nm. However, all the balls have planetary surface structures, most of them rather weak, of about 100 nm lateral extension. The balls in Figures 4 and 5 apparently have nanoparticles of up to about 100-200 nm attached to their surface. It is characteristic that all the global radii of curvature are positive, while locally the fine scale structures seem to exhibit negative curvature (concave shape).

Factory code	Surface character	Base material	diameter/μm
EXP-SS-3.0-RXG	hydrophobic	polystyrene	3.0
EXP-SA-3.2-RNI	hydrophobic	polystyrene	~3.0
EXP-SS-20.3-RXG	hydrophobic	polystyrene	20
EXP-SS-42.3-RSH	hydrophilic	acrylic polymer	30
EXP-SS-78.1-RXG/71	hydrophobic	polystyrene	76

Table 1: Dynospheres used for seeding in the present investigation of the tensile strength of water.

3. Experimental set-up.

The experimental work was carried out at the Versuchsanstalt für Wasserbau Obernach, Germany (Marschall, 1998) and tensile strength was measured with a Keller vortex-flow nozzle (Keller,1980). In this apparatus the liquid rotates when it enters the nozzle so that the minimum pressure is obtained in the throath at the flow axis. This guarantees that the nozzle wall does not influence the tensile strength measured. The test rig is shown schematically in Figure 6. Tap water is supplied to the system at [1] and natural particles are filtered out in a Millipore filter [2] which is built into a 20 l tank. The filter removes particles larger than about 1 μm. The filtered water is stored in a 30 l main storage tank [3] in which the pressure is controlled by a pressurization and vacuum control unit [13]. (The pressure required is established by gas, but due to the short duration of a tensile strength test the water remains degased except at the very end of a test sequence). The water temperature is kept constant with a cooling/heating system built into [3]. During experiments the valve [21] is closed and the water is led from the storage tank, where the pressure is kept at 4 bar, to the vortex-flow nozzle [5] through a mixing unit [4]. Here particles can be supplied from the 50 ml particle storage tank [16], which is at the same pressure as [3]. The flow through [4] reduces the pressure below that in [3], so that liquid from [16] containing the particles can be mixed into the main flow. The particle flow can be controlled by the needle valve [14]. Attempts were made to measure this flow, but had to be given up due to its fast rate of change during the experiments. Therefore, no information of the rate of supply of the Dynospheres was obtained. From [5] the water passes through a flowmeter [6] and a ball valve [9] which is operated by a computer-controlled step motor. During measurements of the tensile strength this valve is opened in steps to increase the flow velocity and hereby reduce the pressure at the center of the nozzle throath where the first cavitation events are going to take place. If no characteristic cavitation event is recorded at a prevailing flow, the valve is opened one step by the step motor, and a short interval of time is allowed, typically 0.6 s, to achieve equilibrium in the test rig at the increased flow. Then it is again ready for detection of cavitation events.

Cavitation events are detected by two techniques: 1) by the signal from an acoustic sensor that records the sound pulse emitted by the implosion of each cavity when it passes into the diffusor of the vortex-flow nozzle, and 2) by the scattering of a 1 mm diameter laser beam which is emitted along the flow axis of the vortex-flow nozzle from a laser diode in the upstream chamber of the nozzle. When the flow is non-cavitating the beam is recorded by a photodetector at the nozzle axis downstream of the diffuser. The occurrence of a cavitation event at the throath axis interrupts the beam and the event is recorded. The event-signals from each of the two transducers are sent to the computer [17], which is programmed so that a series of successive signals, typically 3, from at least one of the transducers within a suitable time, typically 3 s, is required for accepting that cavitation events characteristic of the tensile strength of the water occur. In that case, the pressure, flow velocity, gas content and temperature recorded at the previous flow step are used to calculate the tensile strength. Isolated cavitation events may be caused by large random nuclei. Such events usually occur at a tensile stress lower than the characteristic tensile strength of the liquid. However, the occurrence of a suitable number of signals within a reasonably short time, and in particular if recorded by both transducers, indicate that the tensile strength is reached. Such groups of signals lead to reasonably reproducible measurements of the tensile strength. When the tensile strength is just slightly exceeded the rate of cavitation events may be so large that blocking of the nozzle flow occurs, and it strongly influences the measurements of pressure and flow. Therefore, pressure and flow data acquired after the tensile strength has been reached lead to a large dispersion of the results. When a measurement of tensile strength has been accepted, the ball valve [9] is closed automatically, and a new experiment is performed with stepwise opening of [9] until the tensile strength is again exceeded.

Parallel to the components [5], [6] and [9] an oxygen meter [7] and a flowmeter [8] are mounted for continuous measurement of the gas content in the nozzle flow. The water that has passed through the nozzle and the oxygen meter is collected in two tanks [10] of each 13 l in which the pressure is 0.2 bar, controlled by [13]. From here the water is either returned continuously to the tank [3] through the main Millipore filter [11] by use of the pump [12], or it is returned without filtering when [3] has emptied. In the latter case the valves [18]-[20] are closed, the by-pass valve [21] is opened and the pressure control unit [13] is used to establish the re-loading of [3] by maintaining 0.2 bar in [3] and applying about 0.5 bar in [10] during the transfer of water.

The vortex-flow nozzle [5] is made from glass, and the occurrence of cavitation can be observed visually or photographed.

4. Experiments

Measurements have shown that the tensile strength of unfiltered, unpressurized tap water is very low due to the presence of random natural particles in the water. Therefore, before experiments were started the water was filtered by circulation for 2 - 4 hours in the whole of the flow system at a pressure of 0.2 bar absolute. Hereby clean water of a low gas content was obtained. It was then prepressurized for 15 minutes at 6 bar. Subsequently tensile strength measurements were started, first with the filtered water itself, the water being continuously circulated and filtered, the pressure being kept at 4 bar in the storage tank [3] and at 0.2 bar in the receiver tanks [10]. After a number of such measurements prepressurization at 6 bar for 5 minutes was made. New tensile strength measurements now generally showed increased strength. When a tensile strength of preferably not less than 1.5 bar was achieved, seeding with Dynospheres was started. The maximum tensile strength obtained for filtered water, degased to about 0.2 bar was P_{ts}=1.9 bar. The water temperature was 15-18 ^{o}C and was kept within ±1 ^{o}C in each of the series of experiments.

In some cases a tensile strength was accepted from events recorded by only one of the transducers during the pre-set time interval. Occasionally the acoustic signals were weak, and only the optical signal was recorded. However, the absence of an acoustic signal might also be caused by the passage of sufficiently large non-cavitating objects, e.g. clusters or clouds of particles, which trigger the optical transducer, but do not cavitate, which results in acceptance of a tensile stress level lower than P_{ts}. If detection of only acoustic signals leads to acceptance, the optical sensor may have suffered permanent blocking, or the cavitation events may have been due to particles passing the nozzle off the flow axis, e.g natural particles of density notably larger than that of water.

The flow circuit with the filter [11] was used when the tensile strength of the water itself was measured, and when seeded water was to be cleaned again. Due to limitations in the amount of Dynospheres available and a too fast consumption of them it became necessary already during the first seeding experiment (with EXP-SS-42.3-RSH) to recycle the water containing the balls from [10] to [3] via the by-pass by use of the pressure control unit.

4a. Seeding with EXP-SS-42.3-RSH Dynospheres

The first series of measurement of tensile strength was made with Dynospheres EXP-SS-42.3-RSH. These balls were almost spherical and with only weak planetary surface corrugations in the 100 nm range. They were characterized by the manufacturer as hydrophilic and were measured in our laboratory to be of a diameter of 30 μm, Figure 3. In Figure 7 the obtained tensile strength results are shown vs. the number of the experiment in each of the successive series, separated by pressurizations (indicated by *p*), recycling processes (indicated by *r*) and/or by changes of the state of seeding. The states of seeding divide the graph into four major sections. Note that the 1st axis indicates the sequental order of the inception measurements and does not contain any time imformation. The time between each measurement and the processing times are very different. The whole sequence of experiments takes about one day. The first section shows the tensile strength obtained during circulation of the filtered water itself by 18 successive measurements. 14 measurements are accepted by both transducers and give a mean value $\langle P_{ts}\rangle$ = 1.33 bar, u($\langle P_{ts}\rangle$) = 0.10 bar. In these measurements each of the cavitation events leading to acceptance of the recording as representing the tensile strength were clearly discernible (time intervals of the order of 1-2 s), i.e. there were few natural nuclei large enough to cause cavitation.

In the second section a total of 31 measurements of tensile strength are presented. During these the Dynospheres were seeded into the flow from the particle storage tank [16]. During seeding with these Dynospheres a cascade of cavitation events occurred when the tensile strength was reached, and the numerous cavitation events were directly visible at the nozzle throath. During the first 19 measurements the water was continuously returned to the storage tank [3] via the filter [11] and the pump [12] so that the Dynospheres were filtered out. Due to the fast consumption of the balls the filtering had to be stopped, but the seeding was continued until the tank [3] was empty of filtered water. During this time the last 12 measurements in the second section were made. In this section of experiments a number of low tensile stress events were recorded by only one of the transducers. These are considered to be due to alien particles mixed with the Dynospheres in the particle storage tank or to clusters of Dynospheres. Therefore, all single-transducer events are disregarded. The mean tensile strength calculated from the 13 events detected by both transducers is $\langle P_{ts}\rangle$ = 0.87 bar, u($\langle P_{ts}\rangle$) = 0.06 bar.

The third section shows four series of measurements between which the seeded water was recycled from [10] to [3] via the by-pass. After each recycling the water was prepressurized, but the time used for this process allowed some of the Dynospheres to settle, and this may have led to a loss of particles. The recycling itself probably increased the number of large, uncontrolled particles in the volume of water. Therefore, the two events at 0.01 bar and 0.18 bar tensile stress detected by both transducers as well as those by only one transducer are considered to be false. The remaining 8 measurements recorded by both transducers give $\langle P_{ts}\rangle$ = 0.88 bar, u($\langle P_{ts}\rangle$) = 0.09 bar.

The fourth section shows an increase of the tensile stress when filtration is again started.

4b. Seeding with EXP-SS-3.0-RXG and EXP-SA-3.2-RNI Dynospheres

The EXP-SS-3.0-RXG and EXP-SA-3.2-RNI Dynospheres, Figures 1 and 2, were close to 3.0 μm in diameter. While the EXP-SS-3.0-RXG balls were almost spherical and with only very weak surface structures of a lateral extension of about 100 nm, the EXP-SA-3.2-RNI balls had a major convex deformation from spherical shape and a number of "mountains" in the 200 - 300 nm range on a surface with pronounced corrugation of a scale of about 100 nm. These balls were characterized as hydrophilic and to avoid clustering, the particles (which were received in a 10% sodium dodecyl sulphate-water solution) were mixed directly into the water of the storage tank [3] after the water had been degased and cleaned by circulation through the main filter [11]. With both types of balls the large number of small particles in the water caused a scattering of the laser beam, irrespective of the flow. Hereby a permanent triggering of the optical cavitation event sensor took place. Therefore this sensor was turned off while the 3 μm balls were investigated and only the acoustic sensor was used. The tensile strength measurements recorded by that sensor were not discernible from those measured on the filtered water itself. Therefore, it is concluded that the 3 μm Dynospheres, though hydrophobic and about twice the size of the largest natural particles in the water, were too small to reduce the tensile strength below that set by the natural particles remaining after filtration.

4c. Seeding with EXP-SS-78.1-RXG/71 Dynospheres

The hydrophobic EXP-SS-78.1-RXG/71 Dynospheres were measured to be of a diameter of 76 μm, figure 5. For the experiments with these balls the water was first filtered by circulation through the main filter [11]. During this process it was prepressurized 3 times and its tensile strength was measured, the mean value of signals detected by both transducers being $\langle P_{ts}\rangle$ = 1.23 bar, u($\langle P_{ts}\rangle$) = 0.07 bar. The measurements are shown in the first section of Figure 8. Then the Dynospheres were mixed directly into the water of the storage tank [3] and its tensile strength was measured while [3] emptied into [10]. Repeated recycling transfers of the seeded water were made from [10] to [3], but without prepressurization in order to minimize sedimentation and clustering of the particles. These measurements are shown in the second section of Figure 8. A large amount of the measurements of cavitation events with these Dynospheres were recorded only by the acoustic sensor. This is interpreted to be due to off axis cavitation. Only cavitation events based on acoustical as well as optical acceptance have been used for calculation of the mean tensile strength $\langle P_{ts}\rangle$ = 0.48 bar, u($\langle P_{ts}\rangle$) = 0.07 bar. As expected the tensile strength is significantly lower than with the smaller, hydrophilic EXP-SS-42.3-RSH. Finally, tensile strength measurements during circulation and filtration in [11] were made. The tensile strength increased and the percentage of events based on a single detector decreased as shown in the third section of Figure 8.

4d. Seeding with EXP-SS-20.3-RXG Dynospheres

The hydrophobic EXP-SS-20.3-RXG Dynospheres were measured to be of a diameter of 20 μm, Figure 4. In this experiment, for which the results are shown in Figure 9, the water was first filtered by circulation through [11] (first section, Figure 9), and in this process it was prepressurized 3 times and its tensile strength was measured 28 times, during which a considerable increase of tensile strength was achieved. The main group of the measurements came up to about 1.7 bar, and the drop-outs rose to about 1.1-1.2 bar. Then Dynospheres were mixed directly into the water of the storage tank [3]. Its tensile strength was measured while [3] emptied into [10] (second section, Figure 9). Repeated recyclings from [10] to [3] were made, but without prepressurization to minimize sedimentation and clustering of the balls. All but one cavitation event were recorded with both transducers. Only one of these is interpreted to be an outlier. The mean tensile strength of the seeded water calculated from 48 measurements was $\langle P_{ts}\rangle$ = 0.72 bar, u($\langle P_{ts}\rangle$) = 0.03 bar, i.e. notably higher than for the larger, likewise hydrophobic EXP-SS-78.1-RXG/71, but lower than for the hydrophilic but larger particles EXP-SS-42.3-RSH. After these experiments the water was again filtered by circulation. The tensile strength increased notably (third section, Figure 9), but not to the level achieved before the seeding with Dynospheres, and it was observed that the number of cavitation events remained large in spite of the filtration. It is conjectured that the Dynospheres now caught at the high pressure side of the filter at only 0.2 bar produced gas nuclei which could penetrate the filter and survive after being pumped to the pressurized storage tank, from which they finally reached the vortex-flow nozzle.

5. Discussion

The measurements on water seeded with Dynospheres of diameters of 20 μm, 30 μm and 76 μm resulted in values of the experimental mean tensile strength $\langle P_{ts}\rangle$ = 72 kPa, 87 kPa and 48 kPa, respectively, Table II. The table also gives the much lower values calculated for perfectly hydrophobic spheres, or vapour cavities of the same sizes $(P_{ts})_{R,\mathrm{th}}$. The experimental values can be ascribed to attached, hemispherical vapour cavities of radii $\langle S_{min}\rangle$ = 2.0 μm, 1.7 μm and 3.0 μm, respectively, calculated from

$$P_{ts} = 2\gamma / S_{min} = -(p_\infty - p_v)_{\mathrm{crit}} \qquad (2)$$

These radii are notably smaller than the radii of the balls themselves, but no surface structures of this size are found on the balls. Only structures in the 100 nm range are characteristic.

It is assumed that on each ball these structures have lead to the development of numerous adjacent small-scale voids, which have grown due to pressure reduction and have merged into the notably larger vaporous voids that eventually determine the tensile strength resulting from the ball. The number of merging small-scale voids apparently decreases with an increase of the global, positive curvature of the ball surface, dependent on the character of the ball surface. Even though the balls globally are almost identical in each batch, the tensile strength of the seeded water is found to be a statistic quantity.

This is plausible because the small-scale structures are stochastic. Table II gives the mean tensile strength $\langle P_{ts}\rangle$ found from the measurements and the experimental uncertainty u(P_{ts}) of the individual measurements as well as that of their mean value, u($\langle P_{ts}\rangle$).

diameter/surface μm	$(P_{ts})_{R,\mathrm{th}}$ kPa	$\langle P_{ts}\rangle$ kPa	u($\langle P_{ts}\rangle$) kPa	u(P_{ts}) kPa	S_{min} μm
3.0 / hydrophobic balls	100	? (>150)			
3.0 / hydrophobic balls	100	? (<150)			
20 / hydrophobic balls	15	72	3	17	2.0
30 / hydrophilic balls	10	87	6	21	1.7
76 / hydrophobic balls	4	48	7	24	3.0
<1-2 / natural particles		120-150		30-40	1-1.2

Table 2: The theoretical tensile strength $\langle P_{ts}\rangle_{R,\mathrm{th}}$ due to vapour cavities of the same size as the Dynospheres, and the measured tensile strength $\langle P_{ts}\rangle$ of water seeded with Dynospheres. Further the experimental uncertainties u(P_{ts})and u($\langle P_{ts}\rangle$), and the radii S_{min} of attached vapour cavities corresponding to the measured values of tensile strength are given.

The global radius R is the same within 1-2% for all balls in a batch.

The 30 μm hydrophilic balls result in a higher tensile strength than the hydrophobic 20 μm balls, but the increase due to hydrophilicity is moderate. The number of small-scale voids that have to merge to give the measured values of tensile strength is large.

We assume that in the pressurized tanks [3] and [16] small gaseous interfacial voids exist at the surface of the balls and that they are in dynamic equilibrium at the concave surface structures. When a ball moves from the tank to the nozzle throath the pressure drops dramatically within a short time, and the volume of each void expands by increasing the curvature of its gas-water interface. As diffusion of gas in solution is a slow process the content of non-condensable gas in a void is almost constant during its expansion, and it becomes essentially vaporous.

Let us consider a single, axially symmetric depression in a submerged planar solid surface at which an initial void exists and has the water-gas interface (a), Figure 10 A. Now the system is exposed to a pressure drop, and the interface curvature of the void increases. This implicates a decrease of the wetted angle of attachment of the void. To restore force balance the locus of attachment moves towards the liquid space, i.e. away from the concave, hydrophobic region that has nucleated the void, and towards a region of convex surface shape. Here the solid-liquid bonding is strengthened, because the tendency for gas molecules to enter the interfacial liquid and disturb its bonding is reduced. The locus of attachment may move as far as to the locus of maximum positive surface curvature, Figure 10 B. However, the angle φ between the plane of attachment and the solid surface reaches a maximum as the radius of attachment grows, Figure 10 C, and beyond this maximum the expansion of the locus of attachment is retarded unless further increase of the void curvature is achieved. The liquid-gas interface is trapped at a position between the maxima of surface curvature and that of the angle φ, interface (b), Figure 10 A. From here the void eventually expands to a hemispherical form (minimum radius of curvature, S_{min}), while approaching the position of maximum surface curvature, and the critical pressure $p_{\infty,crit}$ is achieved, interface (c) in Figure 10 A. Now the void becomes unstable and grows violently, thus setting the tensile strength due to a single small-scale void. In a fast expansion inertial forces may cause transient expansion of the void beyond its equilibrium dimensions.

Considering real surfaces these have small-scale corrugations all over their surface. Adjacent corrugation structures may share maxima of surface curvature along parts of their configuration, and voids formed at these structures may be close to each other. At exposure to tensile stress the voids expand and adjacent ones may get into contact at these positions. In such cases they merge into significantly larger voids before they reach hemispherical form, Figure 11 A. Thus, the merging of adjacent voids is considered to be responsible for the tensile strength being lower than that calculated from the dimensions of the small scale surface corrugations themselves.

While the initial void formation at individual small scale surface structures is maybe not seriously influenced by the global curvature of the particle considered, the merging of adjacent voids may be impeded if the global curvature is positive and high. Then the planes of attachment of adjacent voids are inclined relative to each other, Figure 11 B, the more the larger the global curvature is, and it becomes increasingly difficult for adjacent voids to merge. On the other hand, merging is strongly facilitated if the global curvature becomes negative. This commonly happens for natural particles, which explains the low tensile strength of plain water which always contain natural particles of highly irregular shape.

In the present experiments it seems that the 3 μm balls were small enough to prevent merging of small scale voids or at least to reduce merging to at most a few, so that the tensile strength of the filtered water remained determined by the notably smaller, but natural nuclei. The larger balls had too small global curvature to prevent merging of considerable numbers of adjacent small scale voids connected to the surface structures of the almost spherical balls.

Acknowledgements

The authors wish to thank the Norwegian Research Foundation for financial support under grant No. 119167/431 making the present experimental study possible. We also express our gratitude to Dyno Particles AS, Norway (now Dynal Biotech) for generously supplying the Dynospheres forming the basis of the project, and to Danfoss A/S, Denmark for lending us equipment for flow measurement. Finally, we are obliged to Mr. Flemming Kragh for specimen preparation and scanning electron microscopy of the Dynospheres used in the experimental work. We thank Dr. Jette Mackintosh for assistance in preparation of the manuscript.

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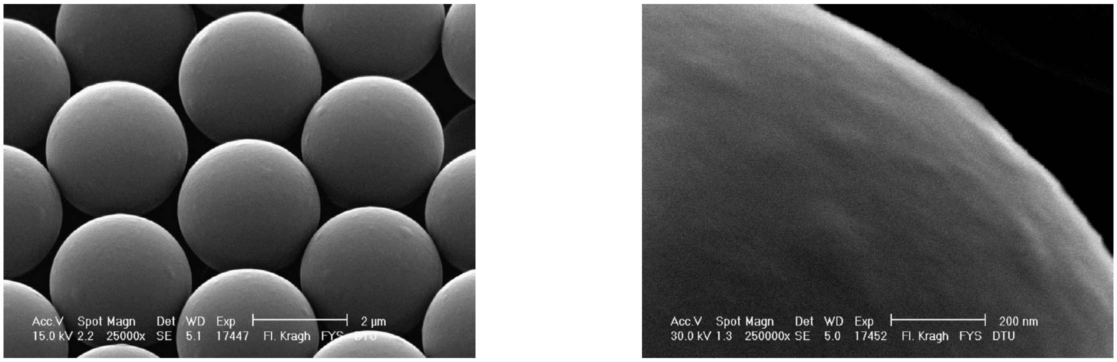

Figure 1. The EXP-SS-3.0-RXG Dynospheres.

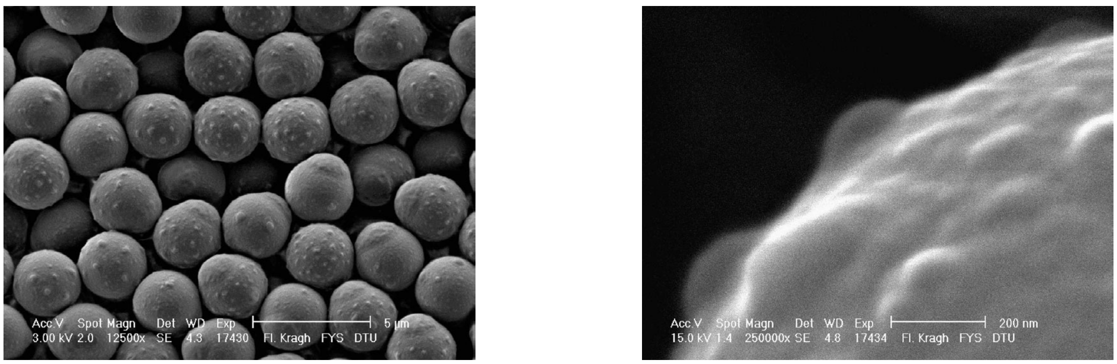

Figure 2. The EXP-SA-3.2-RNI Dynospheres.

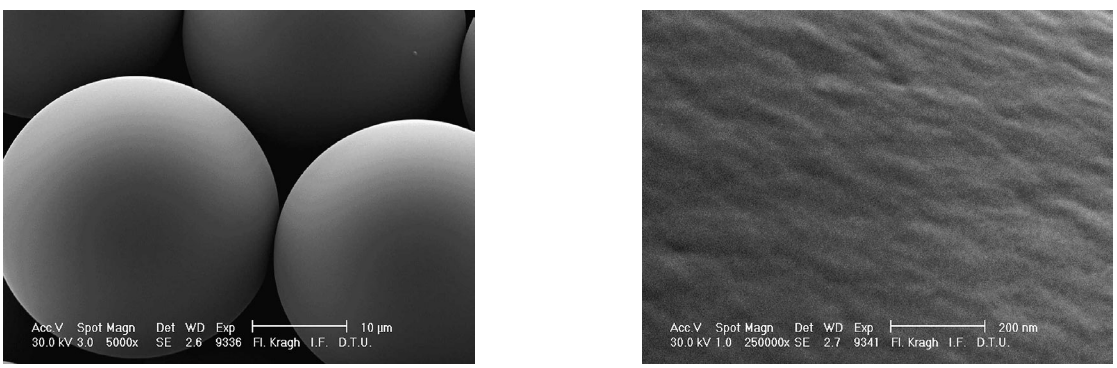

Figure 3. The EXP-SS-42.3-RSH Dynospheres.

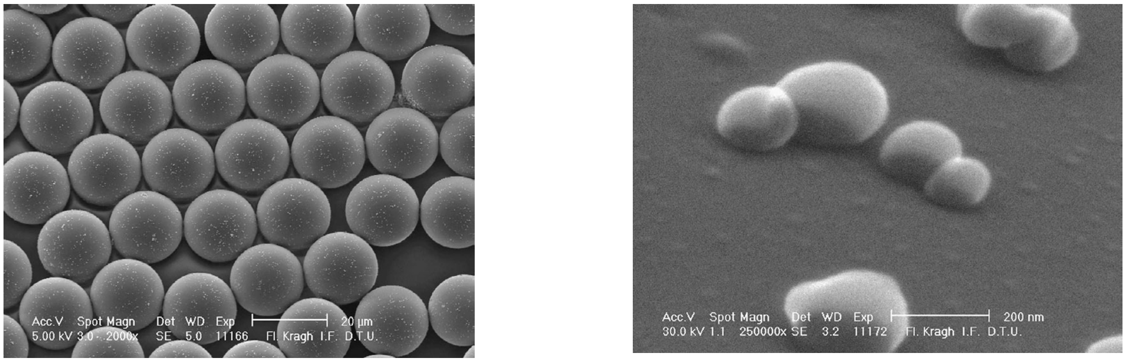

Figure 4. The EXP-SA-20.3-RXG Dynospheres.

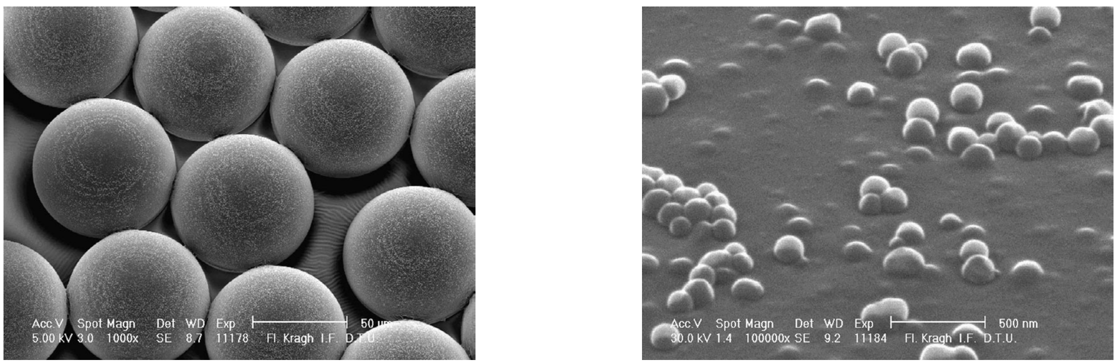

Figure 5. The EXP-SA-78.1-RXG/71 Dynospheres.

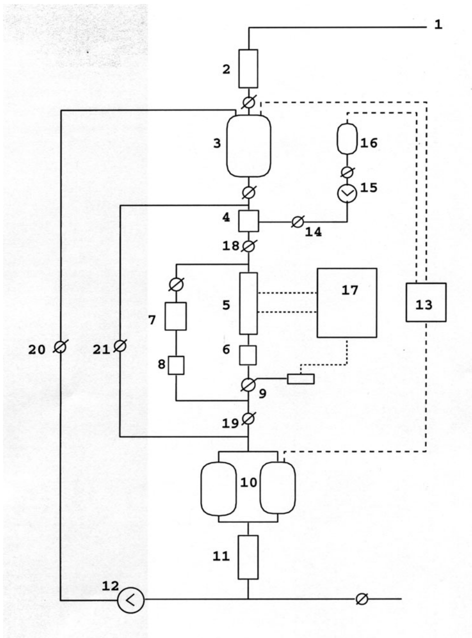

Figure 6. Experimental set-up for tensile strength measurement. [1] Tap water supply, [2] Millipore filter, [3] mail storage tank, [4] mixing unit, [5] vortex-flow nozzle, [6] flowmeter, [7] oxygen meter, [8] flowmeter, [9] ball valve, [10] reservoir tanks, [11] main Millipore filter, [12] pump, [13] pressurization and vacuum control unit, [14] needle valve, [15] flowmeter, [16] particle storage tank, [17] computer, [18]-[21] valves.

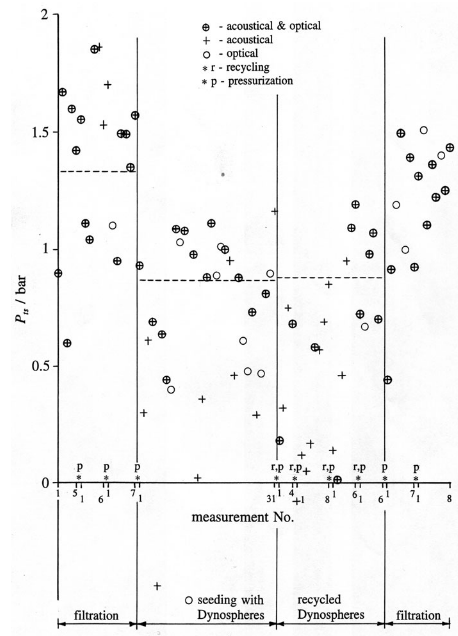

Figure 7. Diagram of the measurements of tensile strength P_{ts} made with EXP-SS-42.3-RSH Dynospheres.

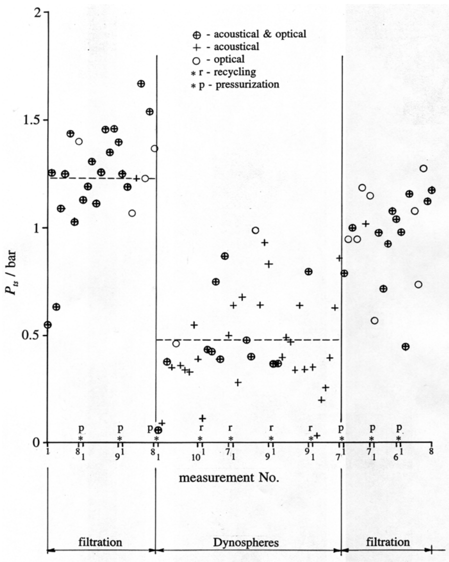

Figure 8. Diagram of the measurements of tensile strength P_{ts} made with EXP-SS-78.1-RXG/71 Dynospheres.

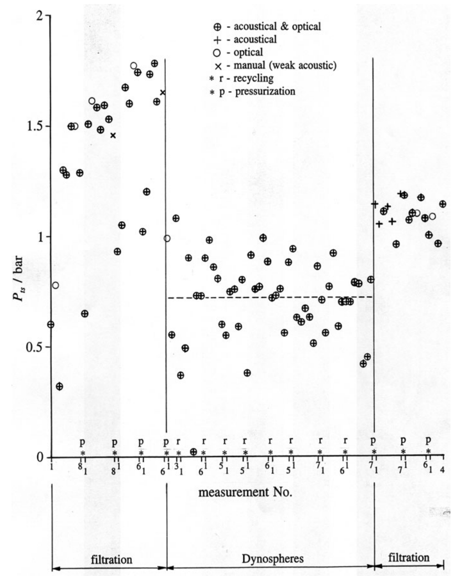

Figure 9. Diagram of the measurements of tensile strength P_{ts} made with EXP-SS-20.3-RXG Dynosheres.

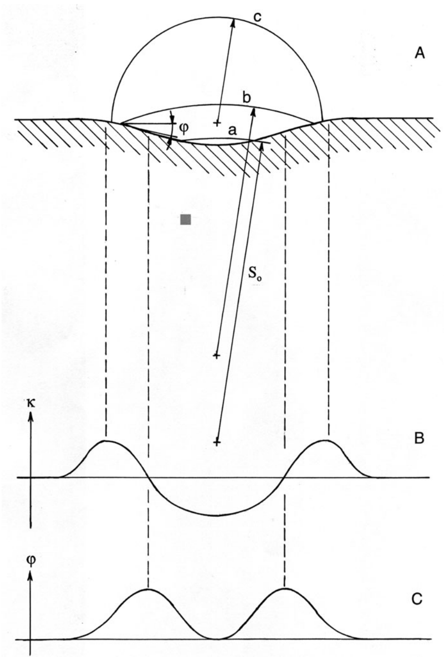

Figure 10. A) The development of a void at a submerged, planar, solid surface with a single axially symmetric depression when it is exposed to tensile stress. (a) initial void interface, (b) interface after radial expansion to the zone of trapping, (c) interface after expansion to hemispherical form. B) Local surface curvature κ. C) Local angle φ of the solid surface with the plane of void attachment (the horizontal plane).

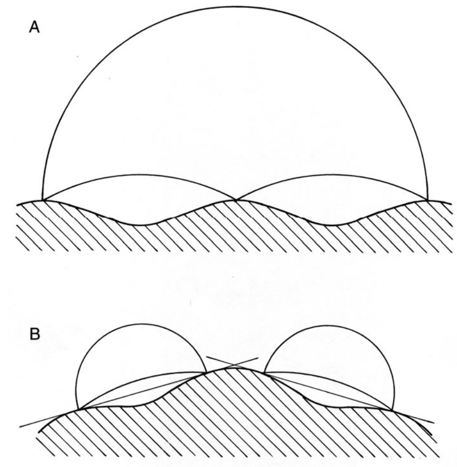

Figure 11. A) Sub-critical voids which merge into a critical cavity at adjacent depression in a submerged, planar, solid surface. The merging results in a tensile strength which is half of that caused by the individual voids, but it is further reduced by the merging of more small scale voids. B) Voids formed at adjacent depressions of lateral dimensions as in (A), but in a solid surface with positive global curvature. Due to the global curvature, the voids do not get into contact when the pressure is reduced, and the critical pressure is determined by the voids individually. The tensile strength is seen to be a factor of about three higher in (B) than in (A).