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Combined Wastewater Disinfection Using Ultrasound

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Abstract

Ultrasound (US), operated at low frequencies, is an effective means for disintegration of bacterial cells: First at low ultrasound doses bacteria flocs can be deagglomerated by mechanical shear stresses. If the US dose is increased ultrasound cavitation impacts on the cell walls such that they are broken. This effect is lethal to microorganisms, hence disinfection takes place. In lab-scale experiments a horn sonotrode operated at 20 kHz was used to sonicate wastewater samples taken from the effluent of a municipal treatment plant. Ultrasound intensity was varied as well as sonication time. Subsequent UV treatment was realised by a low-pressure mercury arc lamp.

When low ultrasound intensities are applied a significant change in particle size distribution (PSD) occurs. Large particles are eliminated almost completely. However, in order to kill microorganisms far higher US intensities are necessary, which at this point in time is not an economical way of disinfection. In combination with UV light applications short US pre-treatment is useful and also provides cost-effectiveness: It could be observed that 30 seconds of exclusive UV treatment were required to reduce the number of fecal coliforms by 3.7 log units, whereas 5 seconds of ultrasonic followed by just 5 seconds of UV irradiation led to the same result, and energy consumption was only 43%.

Obviously low doses of US enable UV light to better achieve disinfection. In that regard the application of ultrasonic pre-treatment replaces sand filtration as solid removal step.

Introduction

At present, it is not imposed by law in Europe that sewage treatment plants' (STP) effluents have to meet microbiological criteria [1]. Nevertheless, authorities have to ensure that in bathing areas concentrations of microbial counts do not exceed certain values given in the EU Bathing Water Directive (76/160/EEC) [2]. Therefore, in many European countries these microbiological water quality criteria are adopted and applied to sewage treatment plants' effluents [3] for STPs that discharge into bathing areas.

As counts of indicator organisms (such as fecal coliforms) are usually not reduced to tolerable levels within a conventional treatment process, an additional subsequent disinfection step is unavoidable (Figure 1).

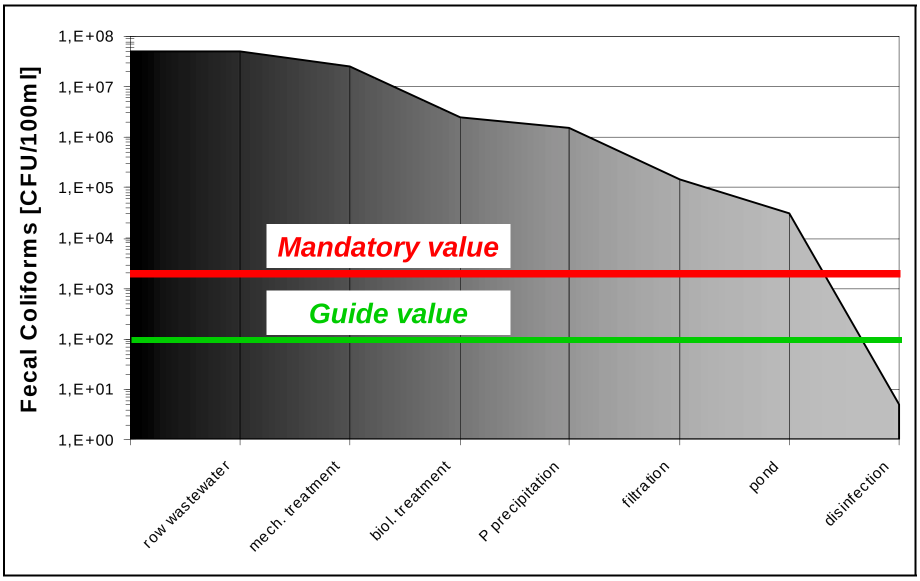

Figure 1: Reduction of fecal coliforms in a STP [4] and bathing water guidelines

Several studies have shown that the efficiency of disinfection methods is highly dependant on the concentration of suspended solids (SS) [5;6], due to the fact that SS can protect bacteria and viruses from being destroyed by disinfectants [7].
For example, the efficiency of ultraviolet (UV) irradiation, is affected by high concentrations of suspended matter [6]: Many small particles tend to scatter UV light, whereas in the presence of big suspended matter bacteria are shaded by or incorporated into "sheltering" flocs (Figure 2). Recent studies [8] have shown that large particles (about 50 µm diameter) are difficult to penetrate so that the required UV demand is raised drastically. Herwig et al. [9] report that particles larger than 50 µm are removed efficiently in a rapid sand filter. When it comes to real-scale applications however, they suffer from various drawbacks (e.g. clogging, algae growth, backwashing). Moreover, rapid sand filters are expensive in construction and maintenance.

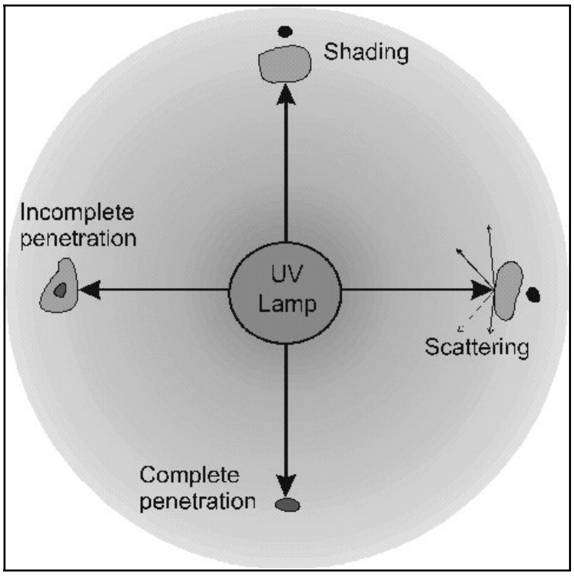

Figure 2: Limitations of UV irradiation

Another attempt to bring down the fraction of big solids present in wastewaters is the application of ultrasound. Numerous articles about the disintegration of biosolids by means of ultrasound have been published [10;11], and detailed descriptions of ultrasound's physical and chemical effects are available [12].

The aim of our experiments was to change wastewater's physical composition (such as "big particles" are transformed into smaller ones) by means of ultrasound and to find out whether these changes in particle size distribution facilitate a subsequent UV disinfection. Therefore, a combination of ultrasonic pre-treatment and subsequent UV disinfection was tested.

Materials and methods

The experimental set-up is depicted in the accompanying schematic Figure 3. In order to avoid sedimentation, a continuous set-up was chosen which also represents a technical system in a better way than a discontinuous system. 10 litres of treated municipal wastewater are stored in a glass bottle and mixed constantly by a magnetic stirrer. A peristaltic pump is used to convey the medium through the system: Firstly, it passes the ultrasound apparatus' processing chamber, secondly, it enters the ultraviolet devise to be exposed to UV irradiation. Samples can be taken after each individual step of treatment.

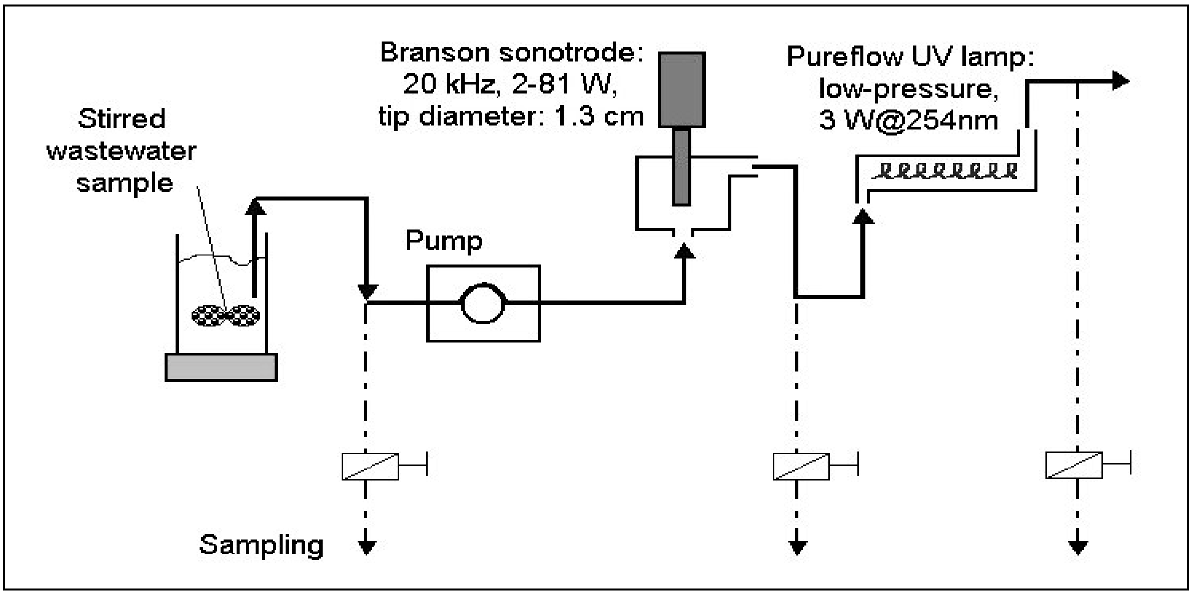

Figure 3: Flow scheme of the experimental set-up

The ultrasound device used was a "Branson Sonifier W-450", a horn sonotrode equipped with a horn tip of 1.3 cm in diameter which is operated at 20 kHz. A typical ultrasonic processing chamber is shown in Figure 4. As strongest cavitation effects in terms of hydromechanical forces can be observed at low-frequency ultrasound application [13] this frequency was chosen. Electrical power in the range of 41 to 154 Watt was applied. To obtain the real energy input into the sample, calorimetric measurements have been conducted [12]: Intensities (power per sonotrode tip surface) ranged from 1.7 to 60.8 W/cm², densities (power per sample volume) ranged from 10 to 400 W/L, respectively.

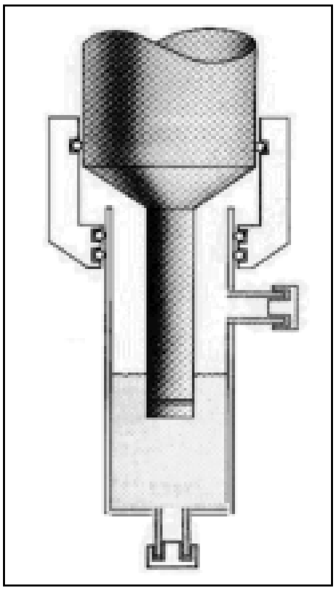

Figure 4: Horn sonotrode with processing chamber

The low-pressure mercury arc lamp (manufacturer: "Pureflow Ultraviolet Inc.", nominal length: 20 cm, diameter: 1.3 cm) is enclosed in a tubular processing chamber (volume: 300 ml). A surrounding thin layer of quartz glass shields the lamp from the sample that flows parallel to the orientation of the lamp. Its energy consumption is 14 Watt of which 3 Watt are emitted at 254 nm (37 µW/cm²@1m), the relevant wavelength for bacteria inactivation.

Particle size analysis was conducted with a Hiac Royco, Model 8000A (equipped with a sampler, model 3000A and a HRLD-150 sensor). In this automatic particle counter a laser diode functions as the illumination source and a photo diode serves as the detector. Particle counts and size distributions are calculated and displayed automatically.
The Spread Plate Technique (for high concentrations of microorganisms) and the Membrane Filtration Technique (for low levels of detectable microorganisms) have been applied (according to the “Standard Methods for the Examination of Water and Wastewater“ [14]). For the enumeration of total germs, total coliforms, Escherichia coli, fecal coliforms and fecal streptococci, specific types of solid agar have been chosen. Results are presented as colony forming units (CFU) per 100ml.

Results and discussion

Ultrasonic modification of PSD

In a set of experiments wastewater samples were treated with ultrasound alone. Ultrasound’s capability to eliminate the fraction of big particles is demonstrated in Figure 5: To better demonstrate the effect that US has on suspended matter, primary effluents were treated first. Samples (STP’s primary effluent) were treated for 20 seconds at various ultrasound densities. Initially, 63 % of the solids in the wastewater sample were bigger than 50 µm in diameter. After a sonication for 20 seconds at 30 W/L, this fraction just accounted for 5 % of the total counts. Increasing ultrasound density further (80 W/L, 220 W/L, 310 W/L), mean particle size hardly decreased.

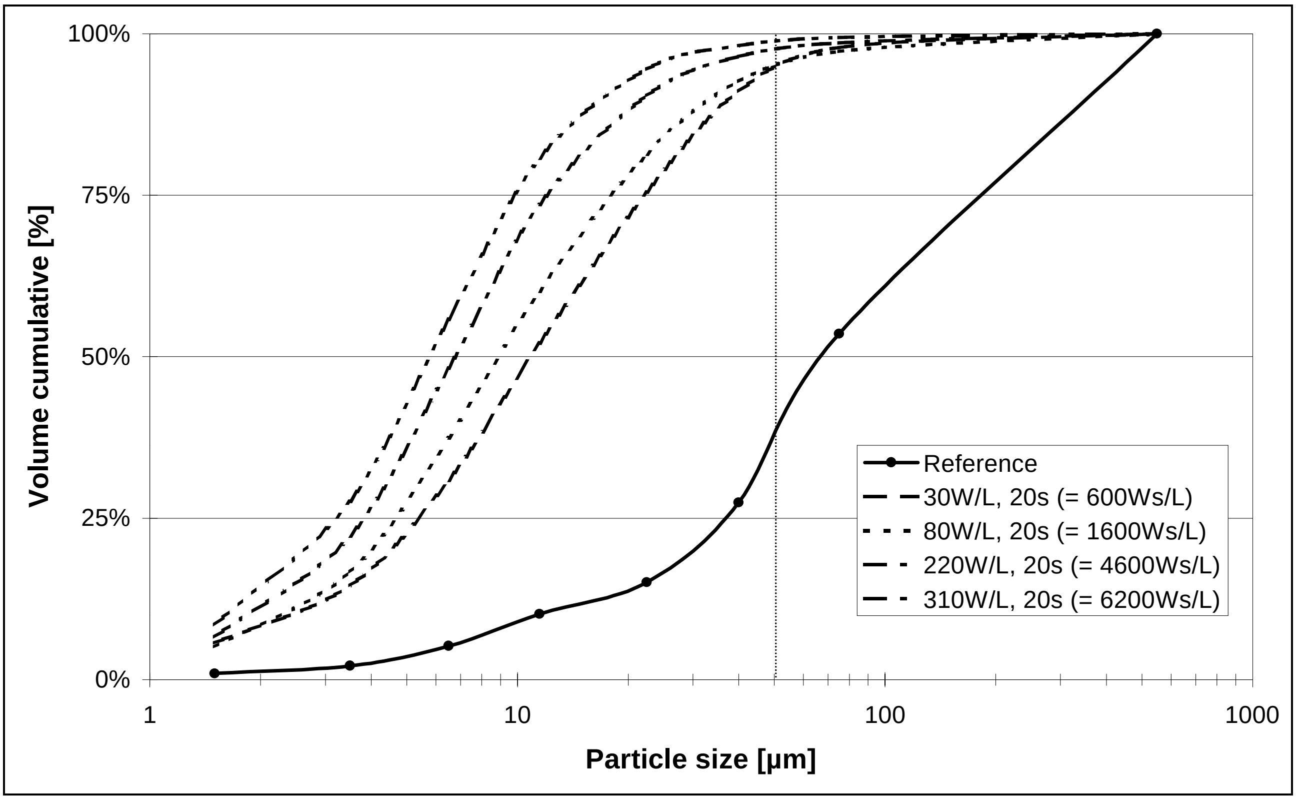

Figure 5: Effect of wastewater sonication (20 s at various densities) on PSD

It stands out that low ultrasound energy (30 W/L) is already sufficient to provoke a clear change in particle composition. Further increased ultrasonic doses have only a marginal effect and the impact on bacterial counts can be disregarded in context with disinfection (< 0.2 log units).

Impact of ultrasound on microorganisms

We observed that a significant reduction of microbial counts was only possible when long sonication times (up to 60 minutes) and maximum US density were applied. Figure 6 shows that a maximum reduction of 2.9 log units of total coliforms was achieved at a dose of 400 Wh/L (60 min at 400 W/L). This is in accordance with the findings of Hua et al. for fecal coliforms [15].

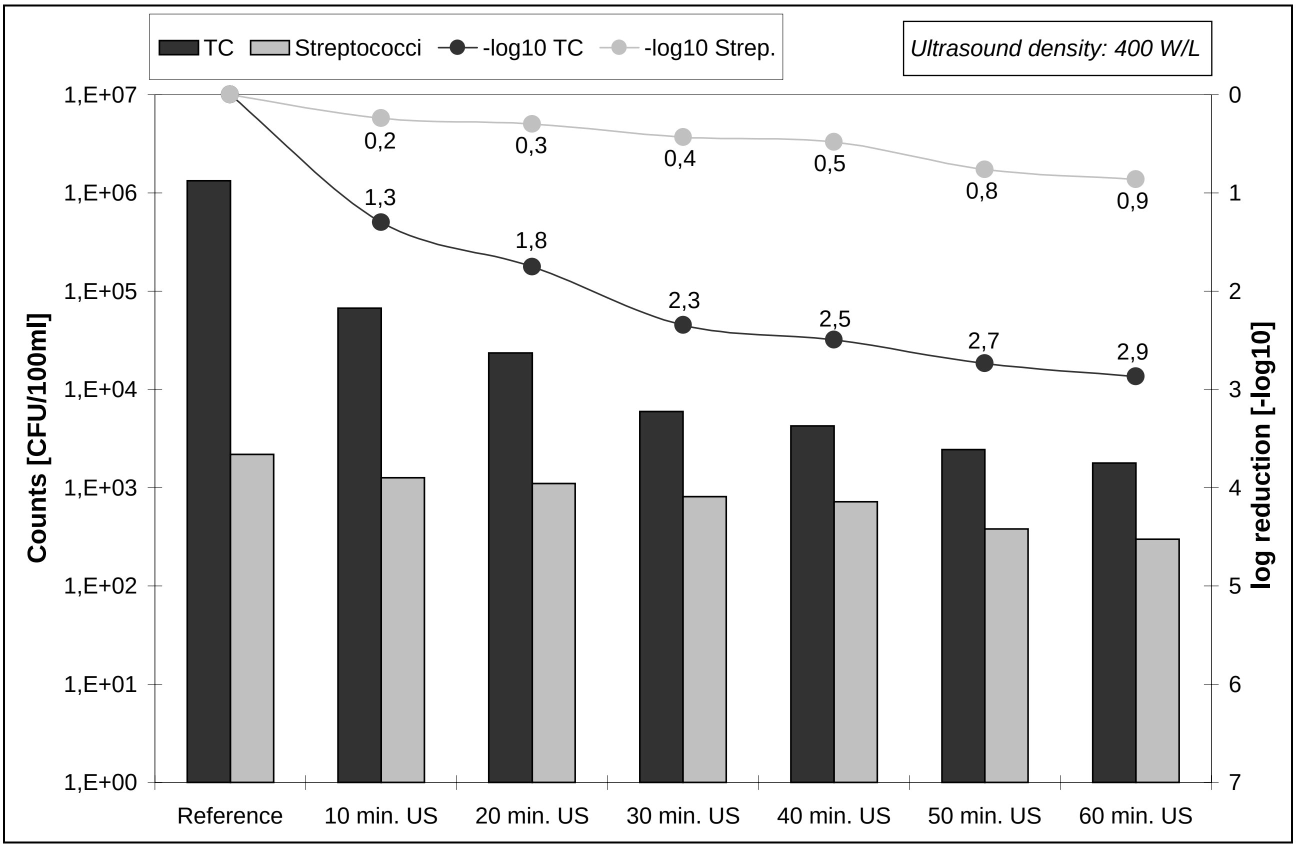

Figure 6: Effect of long sonication on total coliforms (TC) and fecal streptococci

Recent studies have revealed that the enterococci species of fecal streptococci are a more appropriate indicator of fecal pollution, because they show better correlation to human diseases and they survive longer in the water. Moreover, they are more resistant to environmental stress than commonly monitored coliforms [16]. For this reason we did not just focus on fecal coliforms, but also analysed the effect on the less vulnerable group of fecal streptococci. Figure 6 shows that fecal streptococci are significantly less vulnerable to cavitation effects at this dose than coliform bacteria. It might be assumed that this is due to the cell wall structure: Whereas gram-negative enterobacteria are characterised by comparably thin cell walls (100-150 Å), gram-positive streptococci's cell walls are notably thicker (200 Å) [17].

Even assuming that large-scale US devices might be more efficient than lab-scale appliances, energy input doses in the order of several hundred Wh/L are not competitive economically.

Combined wastewater disinfection

We have shown that already low doses of ultrasound changed PSD drastically and per such the protection of single microorganisms is removed. Consequently a following UV application might be significantly promoted. Having this strategy in mind, we applied a combined ultrasound and UV method on secondary effluents and held the energy input low.

Secondary effluents (mean particle size: approx. 10µm) were irradiated by UV light for 5 seconds. The concentration of fecal coliforms (FC) was reduced by 2.5 log units (Figure 7). Prior sonication of these samples for five seconds provoked that "critical particles" bigger than 50 µm could be reduced by 25 % and 60 % (volume related, dependant on the ultrasound dose applied). As a consequence, disinfection efficiency could be improved markedly. At a low sonication level, disinfection rate could be improved by 0.8 log units, for the higher ultrasound level efficiency could be enhanced by 1.2 orders of magnitude (compared with the not pre-treated sample).

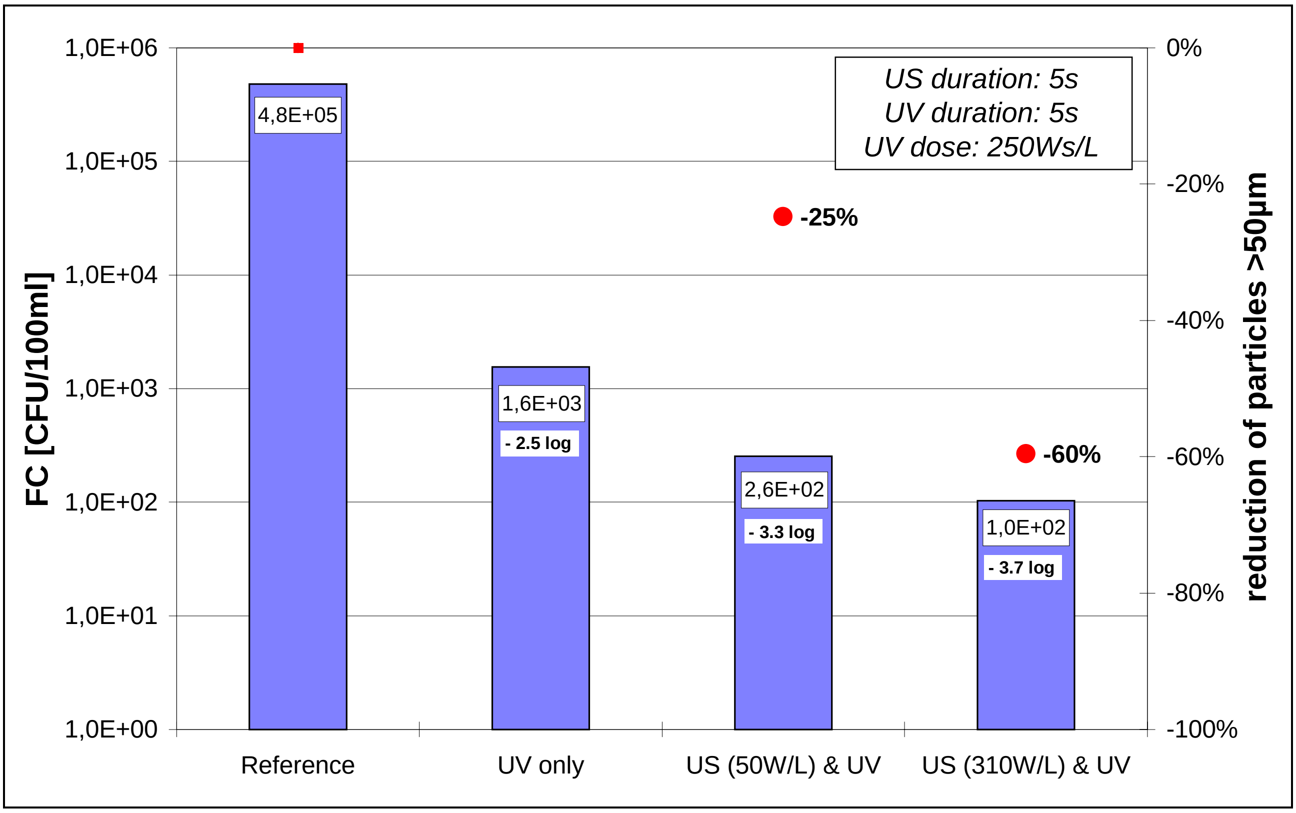

Figure 7: Effect of ultrasonic pre-treatment density (sonication time: 5 s) on reduction of fecal coliforms and on number of particle counts >50µm

We also analysed the effect of an ultrasonic pre-treatment on streptococci (Figure 8): A sample with a high concentration of suspended matter (TSS= 5.2mg/l, mean diameter: 68µm) was treated with UV irradiation for 30 seconds. Ultrasonic pre-treatment for 10 seconds at densities of 170 W/L and 310 W/L, respectively, brought down mean particle size to 35, 20µm, respectively. For both microbiological parameters observed, the ultrasonic pre-treatment has a clear beneficial effect. Disinfection efficiency is by more than 1 order of magnitude higher and the thicker-walled streptococcus species seems to be less vulnerable than E. coli.

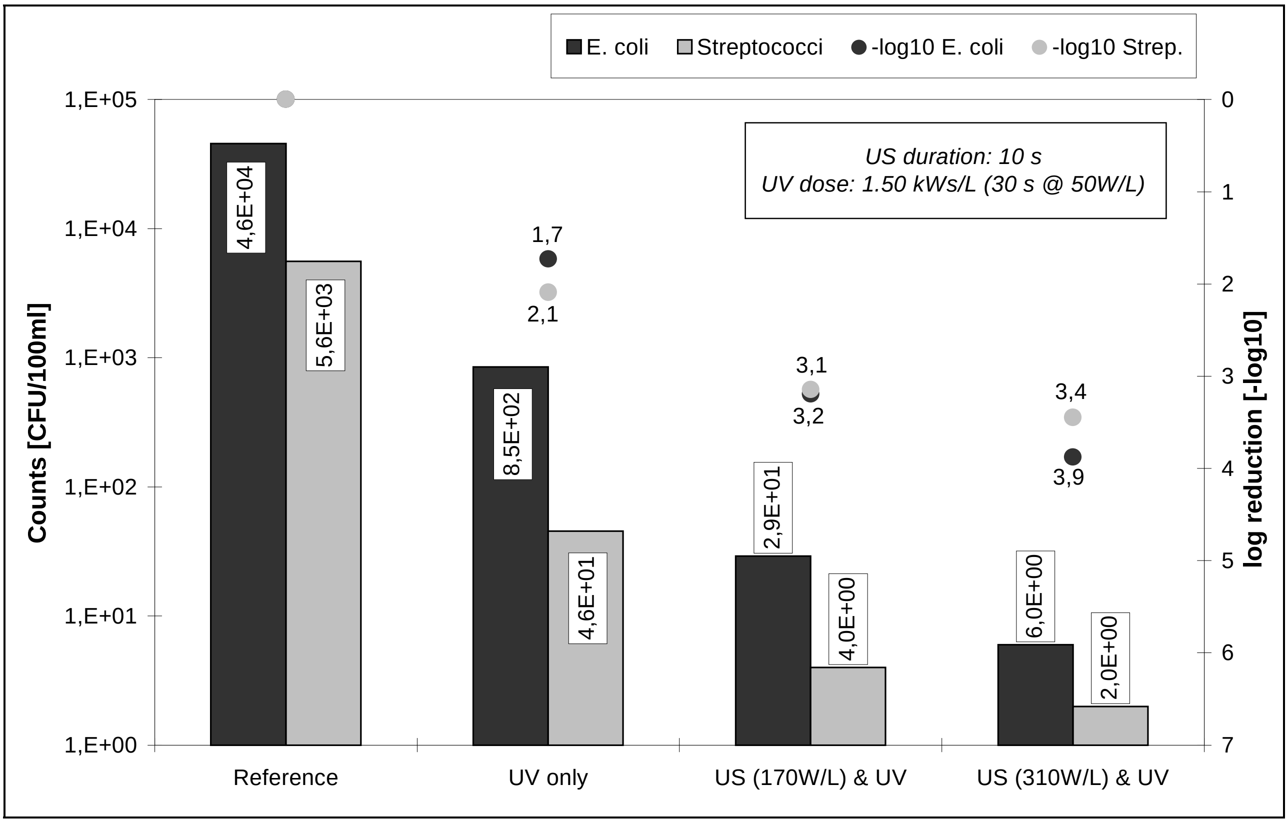

Figure 8: Reduction of E. coli and Streptococci by by ultrasonic pre-treatment for 10 s

Figure 9 demonstrates that a combination of short ultrasonic and subsequent ultraviolet treatment is useful, although specific energy consumption of the US device (80 W/L)was higher than the one of the UV lamp's (50 W/L).

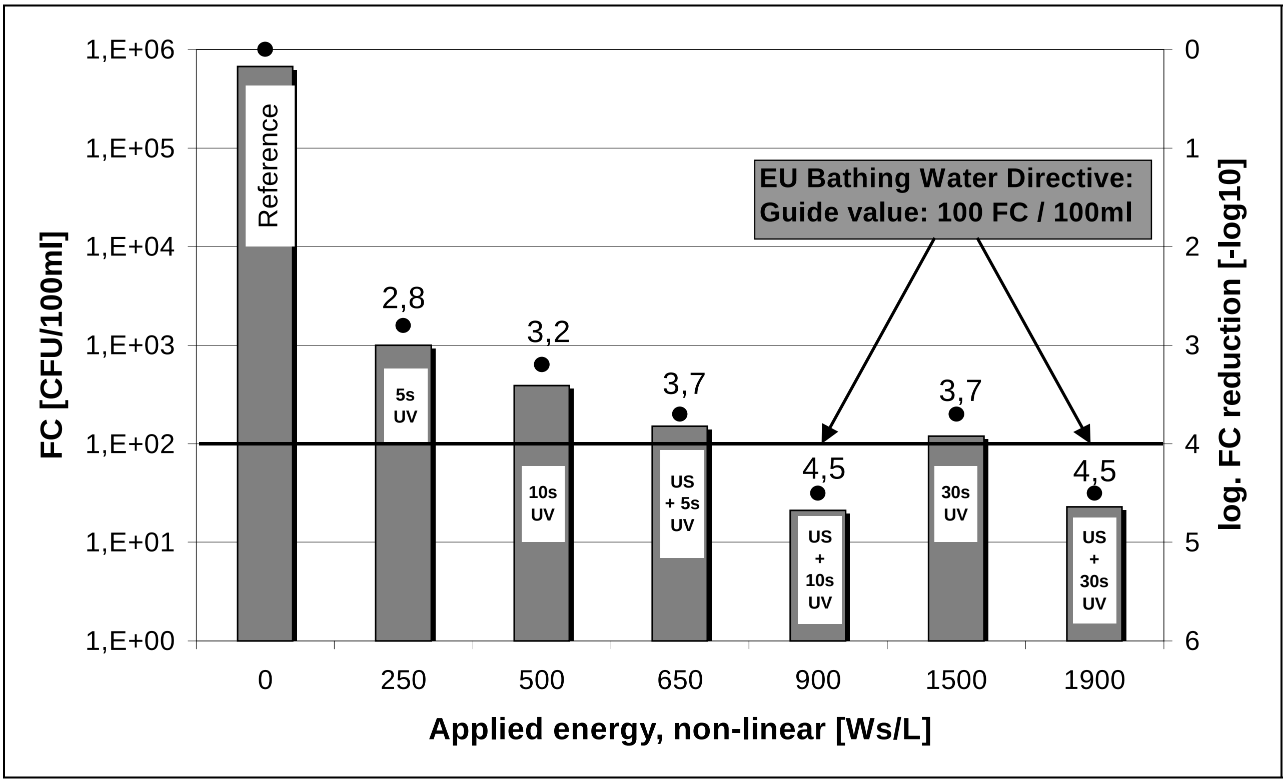

Figure 9: Improved UV disinfection (density: 50 W/L) by ultrasonic pre-treatment (sonication time: 5 s, density: 80 W/L) to meet the Bathing Water guide value

In order to meet the stringent water quality requirements given in the European Bathing Water Directive (guide value: 100 FC / 100 ml), even ultraviolet treatment for 90 seconds would be insufficient. If the sample was sonicated beforehand with a dose of 400 Ws/L, the desired disinfection level could be obtained quite easily: Only 10 seconds of subsequent UV irradiation are sufficient to lower the concentration of fecal coliforms by 4.5 log orders of magnitude, whereas exclusive UV irradiation would only result in a decrease of 3.2 log units. Whereas 5 seconds of ultrasonic pre-treatment and 10 seconds of UV disinfection consume 900 Ws/L to reduce fecal coliforms to a level beneath the critical concentration of 100FC/100ml, an exclusive UV irradiation of as much as 30 seconds is not capable of achieving this goal and consumes even more energy.

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