Wastewater disinfection using ultrasound and UV light

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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 disappear and the average diameter is decreased significantly. 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: Five seconds of ultrasonic treatment followed by five seconds of UV irradiation consumed less energy and led to better disinfection rates than exclusive UV treatment for 30 seconds.

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.
Moreover, first studies on indicators' recovery potential indicate that bacterial regrowth is lower for ultrasonically pretreated samples than for samples exposed to UV light

Introduction

At present, it is not imposed by law in Europe that sewage treatment plants' (STP) effluents have to meet microbiological criteria [EEC, 1991]. 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) [EEC, 1976]. Therefore, in many European countries these microbiological water quality

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criteria are adopted and applied to sewage treatment plants' effluents [Nelle, 1994] 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).

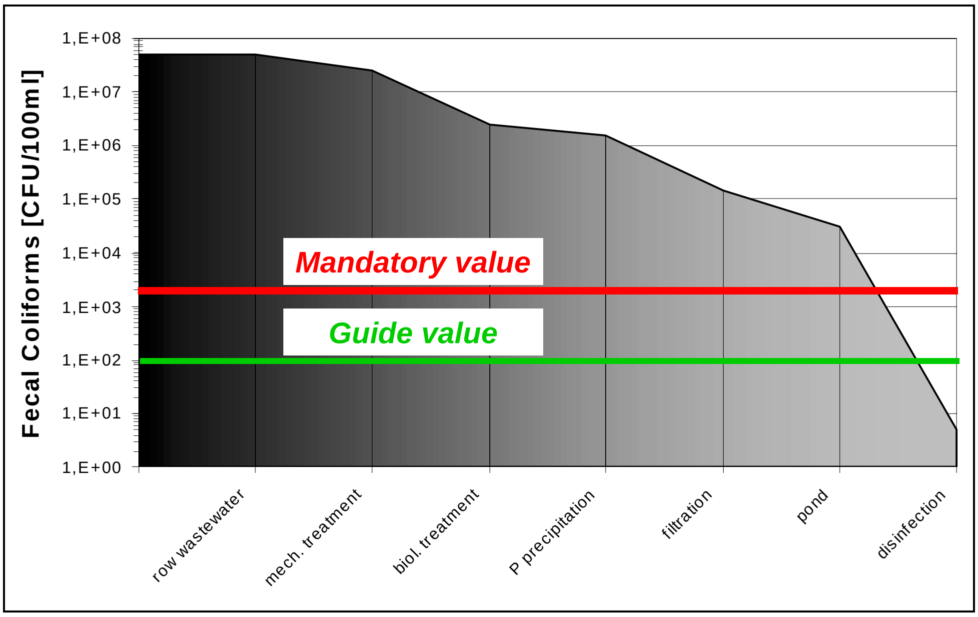

Figure 1: Reduction of fecal coliforms in a STP [Gelzhäuser, 1989] and bathing water guidelines

Several studies have shown that the efficiency of disinfection methods is highly dependant on the concentration of suspended solids (SS) [Narkis et al., 1995; Darby et al., 1993], due to the fact that SS can protect bacteria and viruses from being destroyed by disinfectants [LeChevallier, 1988].

For example, the efficiency of UV irradiation, is affected by high concentrations of suspended matter [Darby et al., 1993]: 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 [Sakamoto and Zimmer, 1997] 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. [2000] 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

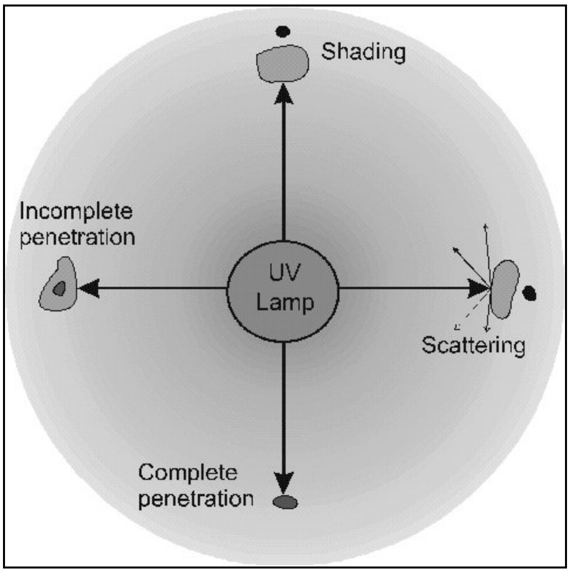

Figure 2: Limitations of UV irradiation

(e.g. clogging, algae growth, backwashing). Moreover, rapid sand filters are expensive in construction and maintenance.

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 [Lehne and Müller, 1999; Nickel, 1999], and detailed descriptions of ultrasound's physical and chemical effects are available [Suslick, 1988].

Due to the fact that wastewater disinfection for reuse purposes as well as for discharge into sensitive receiving waters has been getting more significance lately, our aim is to elaborate ultrasound's potential in this field and to find out under which conditions ultrasound is appropriate to contribute to waste water disinfection.

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.

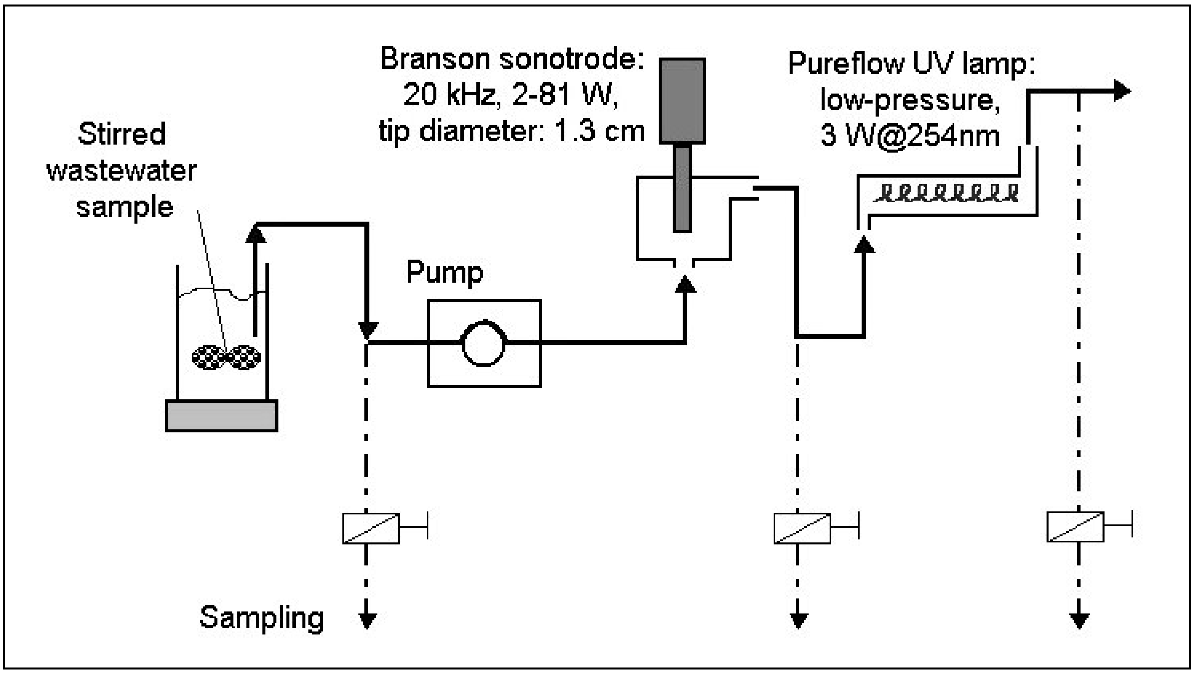

Figure 3: Flow scheme of the experimental set-up

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 [Wiebusch, 1996] 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 [Suslick, 1988]: 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.

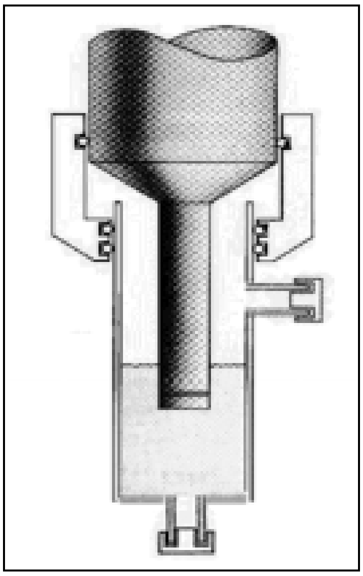

Figure 3: Horn sonotrode with processing chamber

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“ [APHA, 1995]). 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.

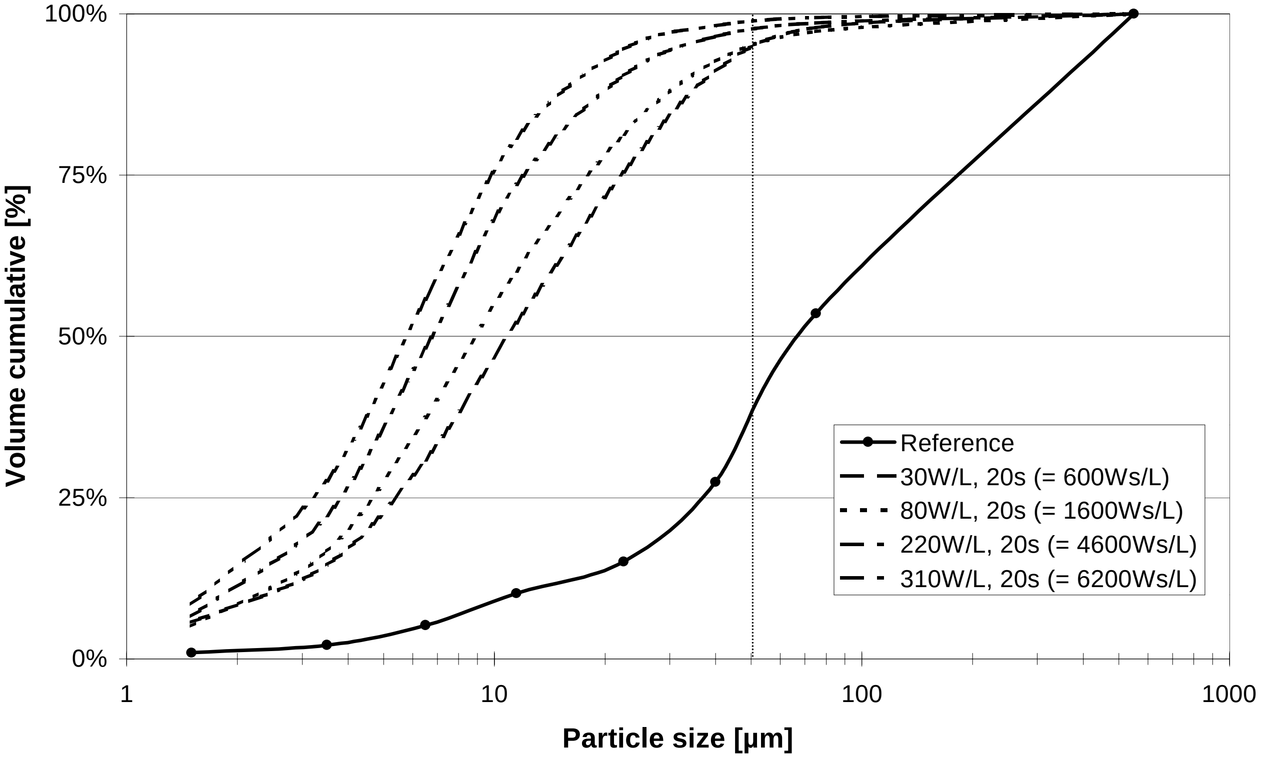

Figure 5: Effect of wastewater sonication (20 s at various densities) on PSD

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.

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 E. coli 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. [2000] for fecal coliforms.

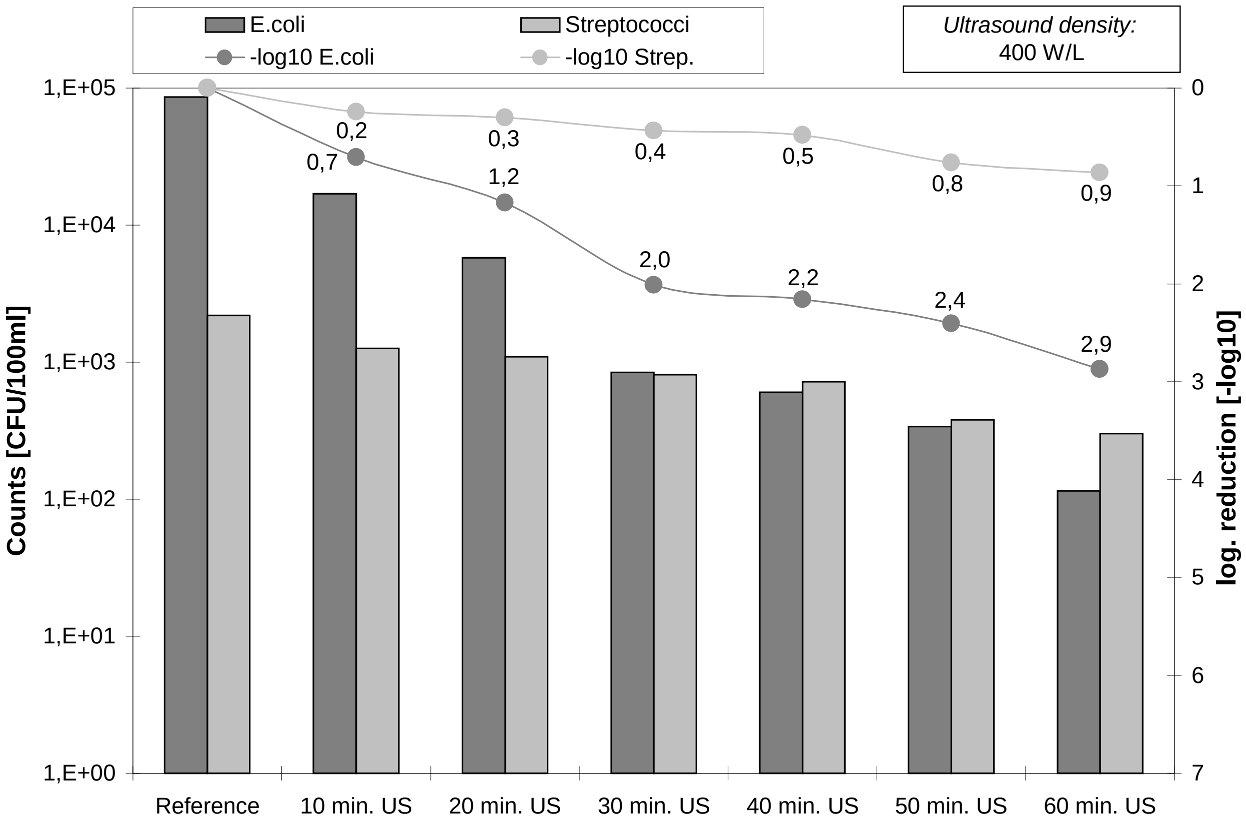

Figure 6: Effect of long sonication on E. coli and fecal streptococci

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 [Figueras, 1997]. 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 at this dose fecal streptococci are significantly less vulnerable to cavitation effects than coliform bacteria. 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) [Cummins, 1989].
When sonicated E. coli as well as fecal streptococci decay kinetics follow a first order reaction behaviour like it is usually observed with other methods. The decay rate constant k is

$$k = \frac{1}{t} \cdot \ln\left(\frac{N_0}{N_t}\right)$$

In our lab test at an applied ultrasound density of 400 W/L we found the following values: $k_{E.coli} = 0.11\ \text{min}^{-1}$ and $k_{strepto} = 0.03\ \text{min}^{-1}$ ($R^2_{E.coli} = 0.96$, $R^2_{strepto} = 0.97$). One might want to compare these results with other data like for UV irradiation: k=0.056 min-1 at 1 µW/cm² or Ozone: k=0.88 min-1 at 0.5 mg/L (Lezcano et al., 1997). However we have to consider that our experiments were a first set of test with lab scale equipment. We know by our experience with ultrasound sludge disintegration that the new full scale 5 kW ultrasound reactors are more efficient than lab scale models. This is the reason why we think that ultrasound disinfection efficiency will be better when full scale continous flow test are performed.

At this point in time however we consider a combination of short ultrasonic application followed by conventional disinfection methods also as promising both in terms of better efficiency/sustainability as well as better economy.

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).

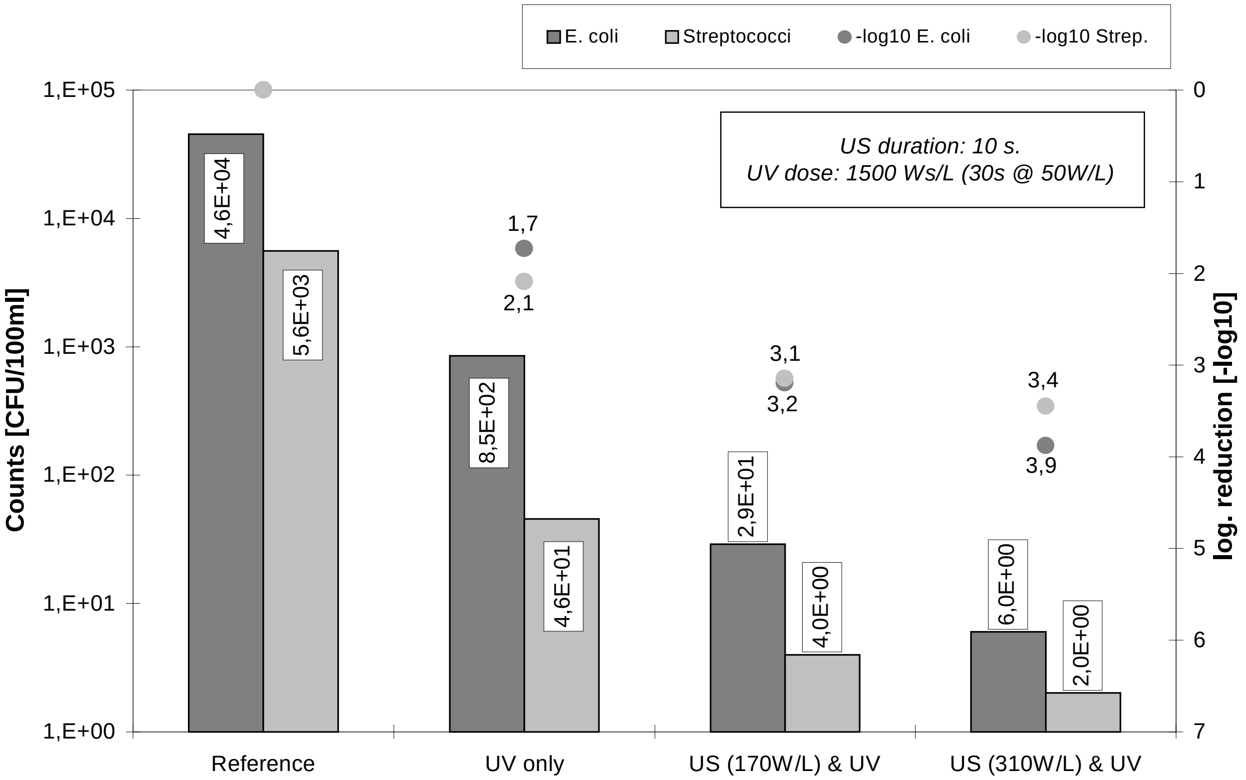

Figure 7: Reduction of E. coli and fecal streptococci by ultrasonic pre-treatment for 10 s followed by UV irradiation for 30 s

We also analysed the effect of an ultrasonic pre-treatment on streptococci (Figure 7): 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 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).
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.

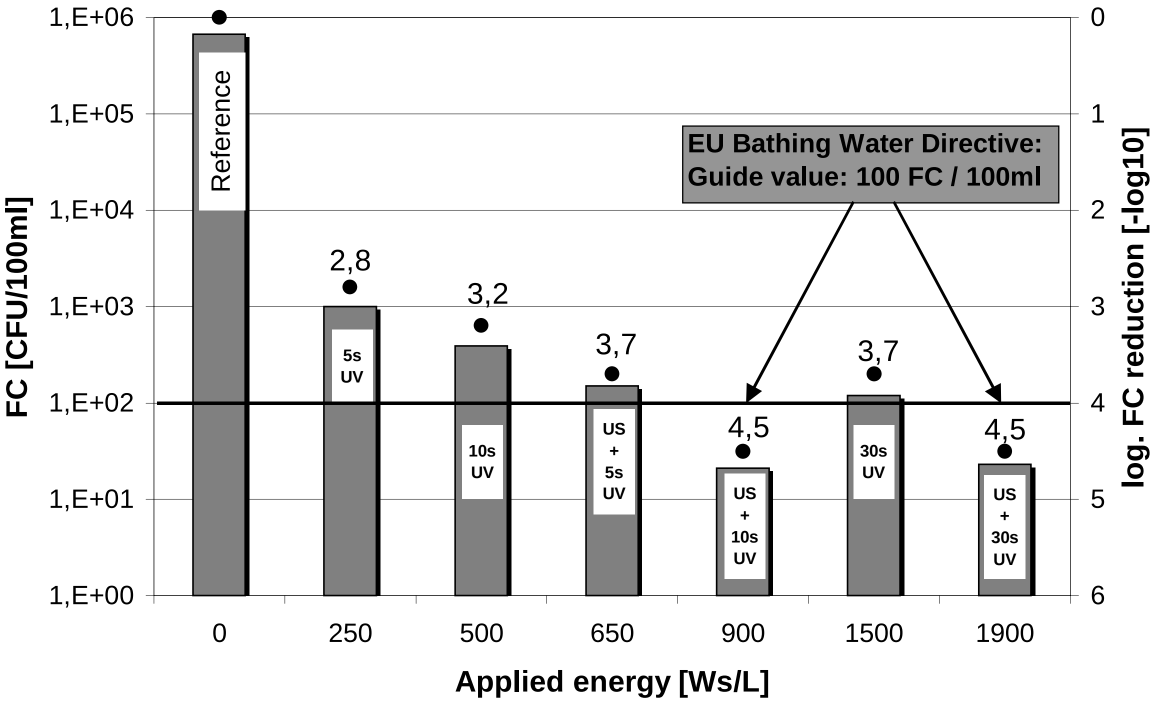

Figure 8: Improved UV disinfection (density: 50 W/L) by ultrasonic pre-treatment (sonication time: 5 s, density: 80 W/L) to meet the Bathing Water guide value (abscissa not to scale)

Does ultrasound improve the sustainability of disinfection?

Bacterial re-growth is a frequently observed phenomenon in potable water distribution systems. When it comes to disinfection of treated wastewater by UV, an argument often cited is the absence of a residual effect and the fact that micro-organisms are capable of recovering [Baron and Bourbigot, 1996].

As UV's primary germicidal effect is due to direct damage of organisms' DNA. Many organisms have developed appropriate countermeasures to prevent undesired mutations or cell deaths caused by DNA changes [Lindenauer and Darby, 1994]. The two different types of repair mechanisms, referred to as "photoreactivation" (in the presence of light) and „dark repair" (in the absence of light), must be considered as disadvantages of UV disinfection.

We looked into bacterial re-growth reactions in samples that were treated with UV light (dose: 1.2 kWs/L) exclusively and compared it with samples that were exposed to a combination of ultrasound and UV (dose: 1.9 kWs/L). Bacterial counts were determined directly after the treatment and after 24 hours of storage in a darkened box at a temperature of 20°C samples. The results are shown in figure 11.

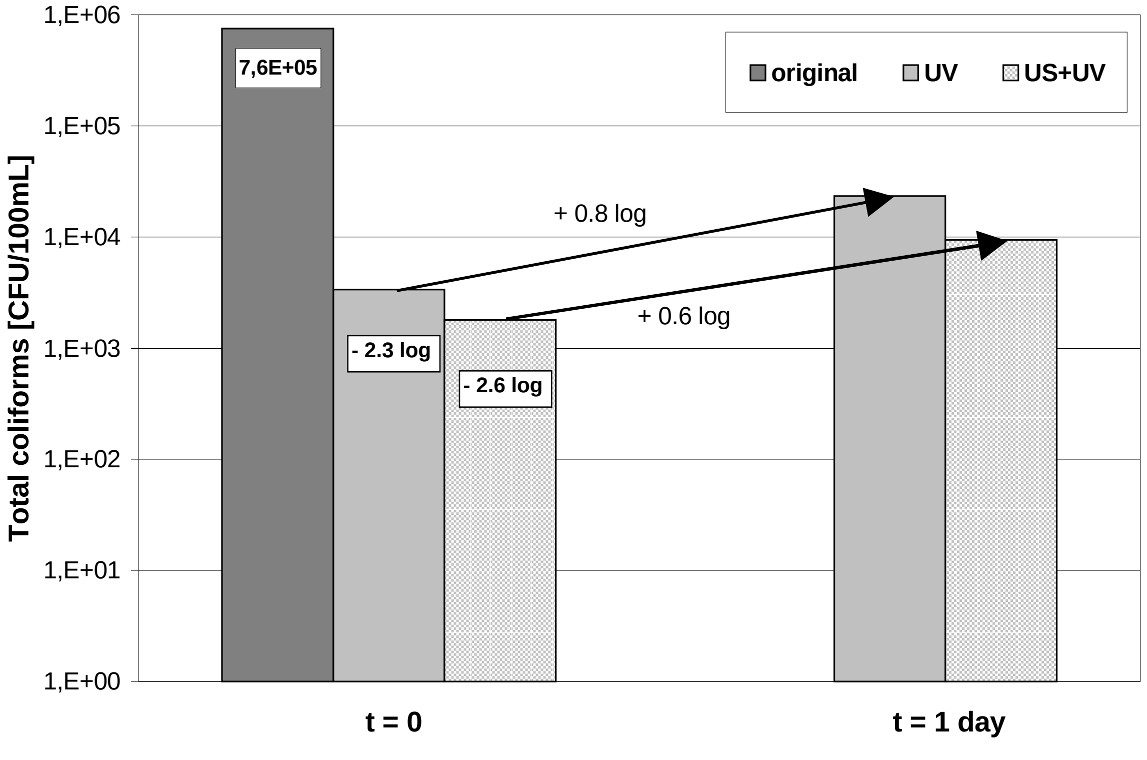

Figure 9: Impact of ultrasonic treatment on re-growth of total coliforms (after 1 day)

We see that both samples undergo a notable recovery: UV treatment of 30 seconds brings down the concentration of total coliforms by 2.3 log units, one day later the level had rises again by 0.8 log. When exposed to ultrasonic and ultraviolet treatment, disinfection efficiency is enhanced and recovery is reduced to 0.6 log. Although these changes are not very drastic, these findings indicate that ultrasonic treatment of waste water might also improve the long-term disinfection impact.

Conclusion

At low ultrasonic doses waste water sample’s physical composition is changed markedly as agglomerates are declumped and subsequent disinfection by other methods like UV is facilitated. In that regard ultrasound is very useful as pre-treatment to conventional disinfection methods like chlorination or UV irradiation.

Ultrasound reactors are very small units that easily can be installed at any place on a treatment plant. In that quality ultrasound can replace sand filters that usually serve as step to remove suspended solids prior to disinfection. Sand filters are large constructions that require considerable investment and operation costs.

There is scientific and economic potential in the development of combined disinfection processes. We will carry on work on a combination of ultrasound/UV and also on ultrasound/chlorination to improve the sustainability and economy of the processes.

In order to definitely damage microbial cell walls higher ultrasound energy input is necessary. Utrasound as an exclusive disinfection method will only be possible if new full scale reactors show significantly better efficiency than lab scale equipment.

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