Practical challenge testing of a ceramic membrane module in a full-scale mobile drinking water treatment system

Christiane Bettin, Boris Schwarz and Anja Kornmueller

ABSTRACT

Challenge testing was carried out of full-scale prefiltration and ceramic ultrafiltration (UF) modules in a mobile drinking water treatment system. Three consecutive indirect integrity tests were performed using naturally contaminated public drinking water, stocking with wastewater as well as addition of powdered activated carbon. Besides checking the removal efficiency and integrity of the ceramic UF membrane, the overall aim of this type test was to prove that the treatment system fulfils the stringent limits of the German Drinking Water Regulation. Up to 4-log removal of different bacteria was achieved by the UF module, whereby log removal values (LRV) were only limited by the bacteria numbers in feed. Complete removal was likewise achieved for spiked particles. High integrity of the ceramic membrane proved that the mobile treatment system can not only be used for drinking water supply for disaster relief worldwide but also for emergency municipal water supply in Germany.

Key words | ceramic membrane, challenge test, integrity, microfiltration, mobile drinking water treatment, ultrafiltration

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INTRODUCTION

Design of mobile drinking water treatment systems have to fulfil special requirements both for the use in industrial and developing countries. First of all, these mobile systems have to meet the required drinking water quality under a wide range of challenging raw water qualities, e.g. high sediment and organic load, turbidity and bacteria numbers. Further specific criteria on system design include easy transportability, robustness, reliability, automatic control, low maintenance, low chemical use, independence on energy source as well as overall sustainability.

For preparation of drinking water from well water and surface water, the mobile drinking water treatment system TWA 15 UF had been developed with a capacity of 15 $m^3 h^{-1}$ and is operated for different applications such as at flood disasters, earthquakes, refugee camps and as a municipal emergency water supply. The system consists of the components: raw water intake, flocculation, adsorption, prefiltration by automatically backflushing disc filters, ultrafiltration (UF), UV disinfection as well as chlorine disinfection for drinking water storage. Due to the modular design, these various process technologies can be flexibly combined with each other depending on the quality of raw water resources.

The first and main barrier for bacteria is the UF membrane. In general the pore size of UF membranes is small enough to ensure complete removal of different microorganisms such as *Cryptosporidium*, *Giardia*, coliforms and total bacteria numbers (Hagen 1998). Besides size exclusion, pore constriction and/or cake layer formation can be additional mechanisms of bacteria removal especially for microfiltration (MF) (Peter-Varbanets *et al.* 2009). In the literature, data on virus (in the range of 0.01–0.1 μm) removal show a wide variation for UF as well as MF. In pilot scale, Hambsch *et al.* (2012) found no removal of spiked bacteriophages by a ceramic MF membrane (0.2 μm pore size) from pretreated dam water while different UF membranes

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with pore sizes of 0.01 μm provided a 2.5–4-log removal. Besides the dependency on the pore size, a significant increase in log removal values (LRV) over 6.4 for viruses can be achieved by inline coagulation before ceramic MF membranes. This coagulation pretreatment aggregates the viruses to a size that exceeds the pore size of the MF membrane (Matsushita *et al.* 2005).

While polymeric UF membranes are well established for drinking water treatment, problems occur in their operation due to fouling and low stability against chemicals and mechanical stress. From aging experiments, Zondervan *et al.* (2007) concluded that main aging factors of a polymer UF membrane were the fouling status and the number of applied pressurized back pulses as well as the combination of both. These factors influenced significantly membrane integrity and led to membrane defects. Therefore, in this mobile drinking water treatment system large-diameter ceramic monolith membranes are used in order to overcome these disadvantages and to reduce the overall footprint of installed equipment. The monolith structure as well as the higher chemical and mechanical resistance of the ceramic membrane facilitates higher membrane integrity.

The German Federal Agency for Technical Relief (THW) has ordered a new series of water treatment systems TWA 15 UF and requested a type test prior to delivery. Besides checking the integrity of the ceramic membrane, the overall aim of the type test was to prove that the TWA 15 UF system fulfils the stringent limits of the German Drinking Water Regulation.

A whole range of direct and indirect membrane integrity tests are described in the literature for drinking water treatment with their individual advantages and disadvantages (Guo *et al.* 2010). As for the application of this treatment system in emergencies, likewise robust and easy applicable membrane integrity testing was required, which can be carried out also in developing countries. Consequently, integrity tests were excluded which, for example, need high-performance analysers or specific cultivation of surrogate organisms for spiking. Different indirect integrity tests were designed which even can be carried out continuously without interruption of system operation. Hereby stored naturally contaminated public drinking water, raw water spiked with wastewater as well as the addition of powdered activated carbon was applied for challenge testing. For monitoring, the target bacteria as colony-forming units (CFU) and particles as turbidity were measured in the feed and in the permeate of the disc filter and ceramic membrane system. Viruses as smaller pathogens were excluded from the testing due to difficulties in preparation, handling and measuring accurately especially in full-scale and field operations. Likewise nanoparticles as virus-sized surrogates were not applicable due to the need for excessive particle numbers and a special nanoparticle analyser (see Lipp *et al.* 2012). As the pore size of the applied ceramic membrane is in the upper range of UF pore sizes, virus removal by UF alone would depend on the formation of a cake layer on the membrane surface and therefore removal varies during operation. Due to the design and application of this drinking water treatment system the removal of viruses is achieved by the multi-barrier treatment processes including flocculation and especially post-disinfection by UV and chlorine.

METHODS

Test system set-up

From the mobile drinking water system TWA 15 UF, the prefiltration module and one of the three ceramic UF modules were used for the challenge testing. The flow rate was 5 $m^3 h^{-1}$ to the treatment modules. The prefiltration consists of automatically backflushing disc filters (Berkal, VWS Deutschland), which have 100 μm filter fineness. On the up and down side of the discs are grooves, whose dimensions are decreasing from the outside to the inside, by which an indepth-filter effect is achieved.

Figure 1 shows a picture of the UF module consisting of two parallel ceramic membranes. The CeraMem® (VWS) ceramic membrane has a pore width of 0.1 μm and gives a large membrane area in a single membrane module (10.7 m^2, L 864 mm, diameter 142 mm). The UF module was operated in dead-end mode at a flux around 235 L/m^2*h and transmembrane pressure around 0.3 bar.

As raw water supply, a mobile open tank (8 m^3) has been filled with 6 m^3 public drinking water a week before testing. After treatment by both filtration modules the treated water was returned to this tank (recycle operation).

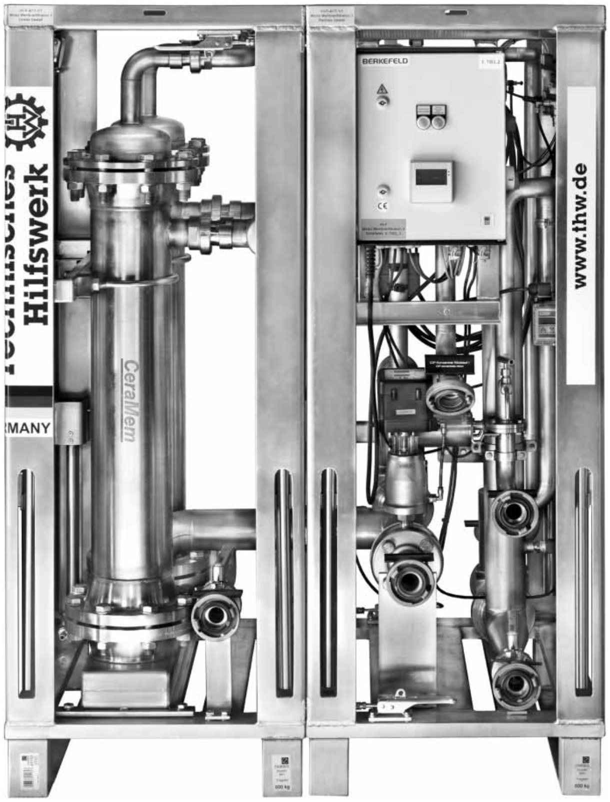

Figure 1 | Picture of the UF module.

Before testing, all piping and treatment modules were disinfected with chlorine solution (50 mg L^{-1} free chlorine) for 30 minutes and afterwards rinsed extensively with drinking water. No free chlorine could be detected at different sampling ports before and during testing.

Examination of naturally contaminated public drinking water

For testing with naturally contaminated public drinking water, the sampling began 30 minutes after starting the pump. Samples were taken after the flow of 2.5 m^3 from the sampling port after the raw water tank, after the filtration of 2 m^3 at the sampling port in the effluent of the disc filter module and after the filtration of 3 m^3 at the sampling port in the effluent of the UF module. Parallel samples were taken from each sample port for each analysis. Besides microbial parameters pH, conductivity and turbidity were also analysed.

Examination of raw water stocked with wastewater

After completion of the drinking water test, 160 L effluent of a municipal wastewater treatment plant was added to the water in the raw water tank. Each two parallel samples were taken from the raw sampling port, after the disc filter and after the UF module. Sampling started 35 minutes after start of the pump. Samples were taken after the flow of 4.5 m^3 from the raw water sampling port, after the filtration of 3.75 m^3 in the effluent of the disc filter module and after the filtration of 3 m^3 in the effluent of the UF module.

Examination of raw water stocked with powdered activated carbon

After completion of the wastewater test and disinfection of the whole testing system with chlorine solution (100 mg L^{-1} free chlorine for 60 minutes), 2.5 kg powdered activated carbon (Pulsorb® BL, Chemviron Carbon, <45 μm: 65–85 w%/w) was added to the water in the raw water tank (0.42 kg m^{-3} activated carbon). For turbidity measurements, samples were taken after the filtration of 2 m^3 in the effluent of the disc filter module and after the filtration of 3 m^3 in the effluent of the UF module.

Sample taking

For the determination of physical parameters, water samples were taken in 100 mL glass bottles. Previously, the glass bottles were rinsed several times with the test water. Samples were directly analysed in a laboratory on site.

For the determination of microbial parameters each sampling port was rinsed by repeatedly opening and closing and flamed by a gas burner. Afterwards, the sampling port was open again, water was drained for some time and each two parallel water samples were taken in sterile glass bottles and transferred to an environmental laboratory in the short term.

Analyses

Standard analysers were used for the determination of the physical parameters temperature and pH (Hanna

Instruments pH 211 with pH-electrode Sentix), conductivity (WTW Multilab 540, LR 325) and turbidity (2100P ISO, HACH LANGE according EN ISO 7027). Each three parallel analyses were carried out, whereby the standard deviation for all physical parameters was below 1.5%.

For the determination of microbial parameters, the accredited environmental laboratory of the administrative district Celle (Germany) used the following methods:

- CFU at 22 °C in CFU/mL at 22 °C: TrinkwV 1990
- CFU at 36 °C in CFU/mL at 36 °C: TrinkwV 2001
- *Escherichia coli* in CFU/100 mL: DIN EN ISO 9308–1
- Coliforms in CFU/100 mL: DIN EN ISO 9308–1
- Enterococci in CFU/100 mL: DIN ISO 7899–2.

Due to moderate standard deviations for microbial parameters (0–8.3%), mean values were given for the two parallel drinking water samples. Likewise mean values were calculated for raw water stocked with wastewater, although as expected the standard deviation was higher with 0–34.7%.

In parallel, microbiological test systems (IDEXX) were conducted which are used under field laboratory conditions. Colilert®-18/Quanti-Tray® was used for the quantification of *E. coli* and coliforms. This method is approved as equivalent to DIN EN ISO 9308–1 for drinking water analyses in Germany. Enterolert™-E/Quanti-Tray® was used for the quantification of enterococci. The CFU at 22 °C and at 36 °C were determined by the Quanti-Disc® and SimPlate® methods.

RESULTS AND DISCUSSION

Three consecutive challenge tests with different contaminations by bacteria and particles were carried out for removal efficiency and integrity testing. At the beginning of the testing, the stored drinking water in the raw water tank had a pH of 7.96, temperature of 22.9 °C and conductivity of 320 $\mu S\,cm^{-1}$. No significant changes in these parameters could be detected during the test runs.

Bacteria analyses gave comparable results for the standard methods of the environmental laboratory (results shown below) and for the rapid methods (IDEXX), whereby the latter give the advantage of easier applicability on site and faster availability of results.

Naturally contaminated public drinking water

In the first challenge test, the disc filter and the UF module were tested with the stored and thereby naturally contaminated public drinking water. As expected, the faecal bacteria *E. coli*, coliforms and enterococci were not detected in the raw water and consequently not in the effluents of the disc filter and UF module. The inlet numbers of total bacteria with 6,900 (22 °C) and 9,450 (36 °C) CFU/mL were rather high due to the storage time of the drinking water over a week before testing.

Figure 2 gives the total CFU at 22 and 36 °C in the raw water, after the disc filters and after UF. The increase of CFU in the effluent of the disc filter compared to the raw water is a well known phenomenon. It is caused by the indepth filtration effect, by which particles are sheared inside the grooves of the filter discs to smaller particles. This fragmentation leads to a higher quantification in the analysis of CFU because bacteria are attached to particles and a CFU can consist of not only one but a few bacteria.

As shown in Figure 2, the UF module removes completely all bacteria, fully in compliance with the German drinking water (DW) limits of 100 CFU/mL for distributed drinking water. Hereby a LRV over 4 is achieved for total bacteria by the ceramic membrane module.

As with total bacteria, the turbidity is also increased in the effluent of the disc filter compared with the raw water (see Figure 3), which is caused by the above discussed shear stress and the specific higher turbidity of smaller particles. Overall, the UF removes 98% of turbidity to very low 0.02 NTU in the effluent, which is in the range of the detection limit.

Raw water stocked with wastewater

In the second challenge test, the treated raw water was stocked with wastewater. Comparing Figures 2 and 4, it is noticeable that the numbers of CFU at 22 and 36 °C are lower in this test stocked with wastewater than in the previous test with stored drinking water. As described above, before the first test the drinking water was stored for a

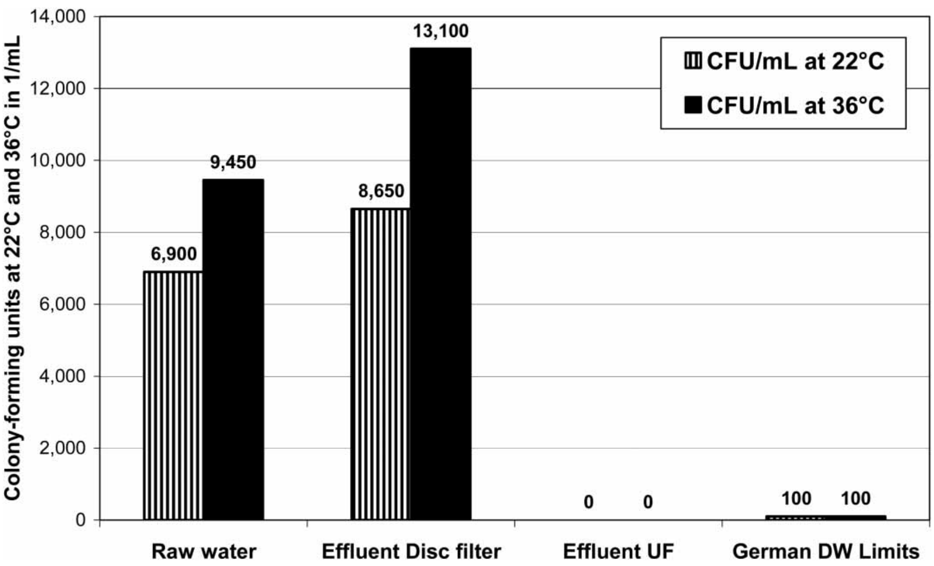

Figure 2 | Total colony-forming units at 22 and 36 °C for stored drinking water as raw water, after treatment by disc filter and after ultrafiltration compared with German drinking water limits.

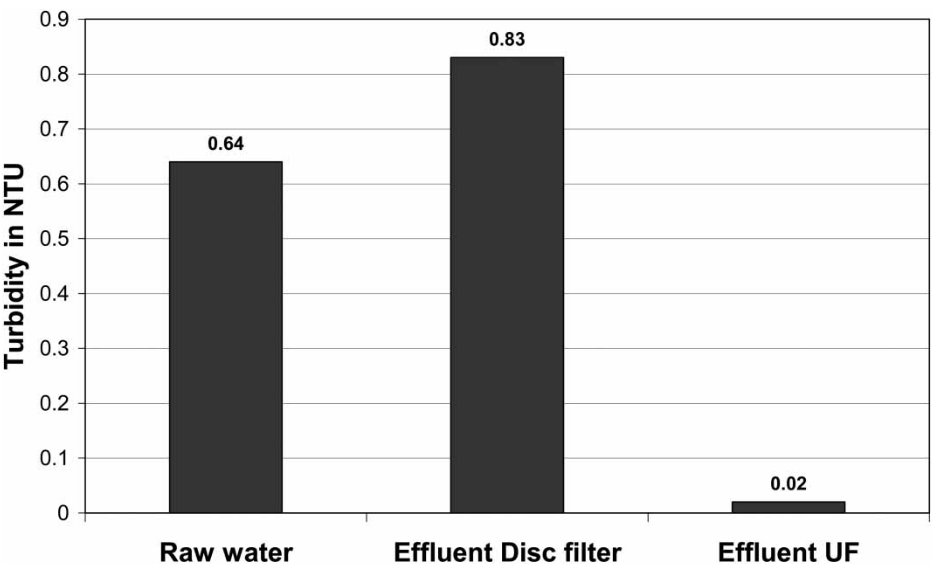

Figure 3 | Turbidity in NTU for stored drinking water as raw water, after treatment by disc filter and after ultrafiltration.

week in the open raw water tank and thereby naturally contaminated by bacteria. Overall 8 m^3 of water were treated during the first test and preparation for this second test. Therefore all bacteria, which were originally in the 6 m^3 stored drinking water, were already completely removed by UF due to the recycling of treated water to the raw water tank. Furthermore, the stocked wastewater was only 2.6% of the volume of the already treated and therefore bacteria free raw water. This fully explains the lower CFU at 22 and 36 °C in this second test.

In the stocking with wastewater, *E. coli* was intentionally used as a surrogate, because its size range of 1–4 μm is a known target organism for *Cryptosporidium* with a size range of 3–7 μm (USEPA 2005). It has to be noted that

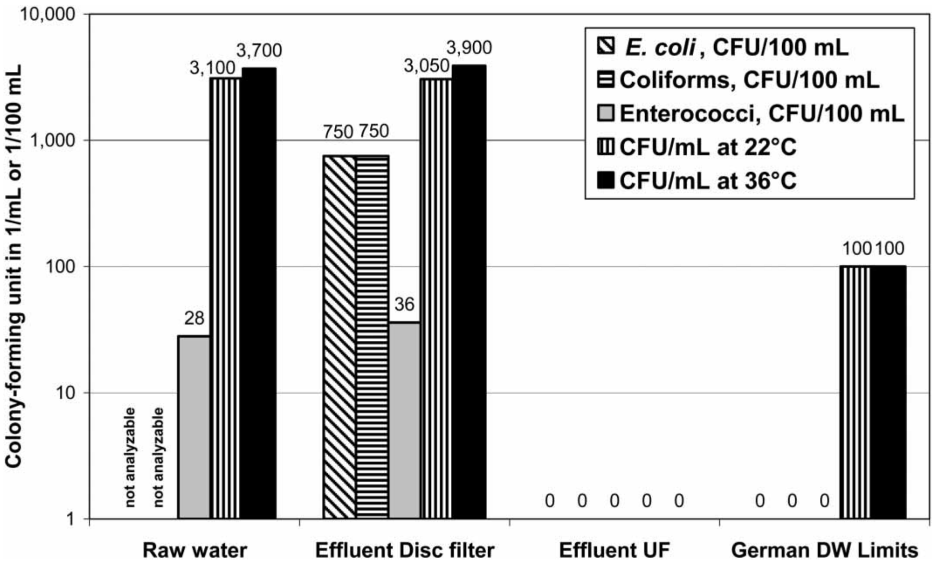

Figure 4 | *E. coli*, coliforms, enterococci and total colony-forming units at 22 and 36 °C in log-scale for raw water stocked with wastewater, after treatment by disc filter and after ultrafiltration compared to German drinking water limits.

E. coli and coliforms could not be identified and counted in the raw water samples due to strong growth (marked as 'not analysable' in Figure 4). However, for the raw water, similar numbers of *E. coli* and coliforms can be assumed as in the effluent of the disc filter, because bacteria are not removed by this coarse prefiltration step. By the following UF, all five microbial parameters indicate a complete removal to zero CFU in the effluent. These results are fully within the German drinking water limits.

Raw water stocked with powdered activated carbon

In the third challenge test, powdered activated carbon was added to the water in the raw water tank. Thereby, the turbidity in the raw water was 248-fold higher than in the test with stored drinking water (compare with Figure 3). In accordance with the particle size of the powdered activated carbon (<45 μm: 65–85 w%/w), only a slight removal of turbidity is achieved by the 100 μm disc filter which can be attributed to the indepth filter effect. The major part of the high turbidity is completely removed by the ceramic UF membrane down to the detection limit achieving a LRV of 3.7. Comparing Figures 3 and 5, the independence of the UF performance on the raw water quality has to be stressed. The very low turbidity in the UF effluent is in accordance with the German Drinking Water Regulation. Low turbidity levels are a precondition for a final disinfection of drinking water, particularly with regard to viruses as the pore size of the ceramic membrane is in the upper range of UF pore sizes, as well as concerning drinking water storage before distribution.

Overall, the results of these three consecutive challenge tests prove the high removal rate for bacteria and particles and therewith the excellent integrity of the ceramic UF membrane module.

CONCLUSIONS

In challenge testing, the ceramic membrane module of a full-scale mobile drinking water treatment system demonstrated its ability to completely remove the target organisms and particles. Up to 4-log removal of different bacteria was achieved by the UF module. As all bacteria numbers in the effluent of the UF were zero, higher LRV would have been reached in case of higher bacteria numbers in the raw water. Improvement in bacteria feed numbers could be achieved by longer storage time (>1 week) or spiking with a higher volume ratio of wastewater provided that is practical.

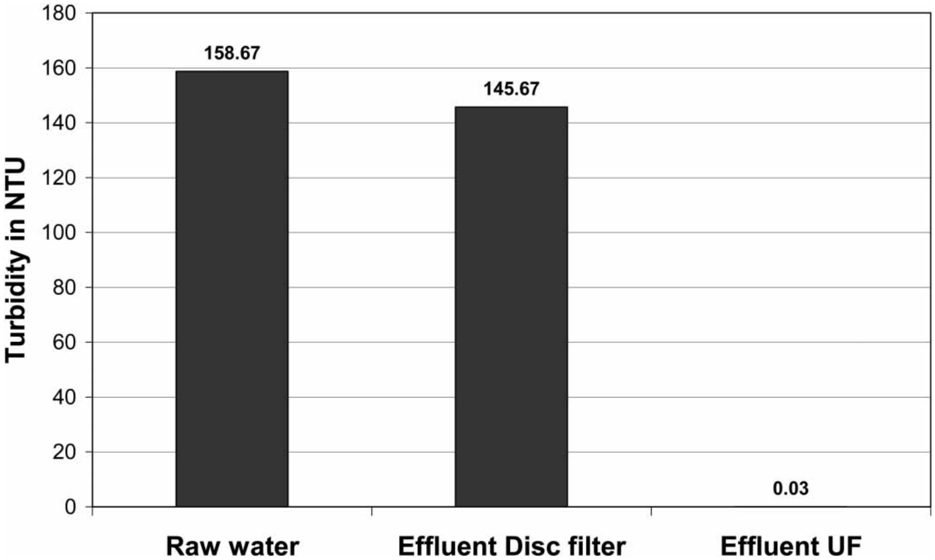

Figure 5 | Turbidity in NTU for raw water stocked with powdered activated carbon, after treatment by disc filter and after ultrafiltration.

Likewise for naturally contaminated drinking water, the turbidity was completely removed by the UF module also under the challenging stocking with powdered activated carbon. For tested bacteria and particles, the UF module showed independence on the raw water quality. Overall these results prove the high integrity of the ceramic membrane and demonstrated that in regard to turbidity and microbial parameters even the stringent requirements of the German Drinking Water Regulation are fulfilled immediately after UF. Therefore, the mobile drinking water treatment system can not only be applied for drinking water supply for disaster relief worldwide but also for emergency municipal water supply in Germany.

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