Ceramic silver-impregnated pot filters for household drinking water treatment in developing countries: material characterization and performance study

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Abstract
The ceramic silver-impregnated pot filter (CSF) is a low-cost drinking water treatment system currently produced in many factories worldwide. The objective of this study is to gather performance data to provide a scientific basis for organisations to safely scale-up and implement the CSF technology. Filters from three production locations are included in this study: Cambodia, Ghana and Nicaragua. The microstructure of the filter material was studied using mercury intrusion porosimetry and bubble-point tests. Effective pores were measured with a mean of 40 μm, which is larger than many pathogenic microorganisms. The removal efficiency of these microorganisms was measured by using indicator organisms; total coliforms naturally present in canal water, sulphite reducing Clostridium spores, E.coli K12 and MS2 bacteriophages. The removal of these organisms was monitored during a long-term study of several months in the laboratory. Ceramic silver impregnated pot filters successfully removed total coliforms and sulphite reducing Clostridium spores. High concentrations of Escherichia coli K12 were also removed, with log(10) reduction values consistently higher than 2. MS2 bacteriophages were only partially removed from the water, with significantly better results for filters without an impregnation of colloidal silver. During this study the main deficiency of the filter system proved to be the low water production; after 12 weeks of use all filter discharges were below 0.5 Lh⁻¹, which is insufficient to provide drinking water for a family.

Keywords Ceramic; developing countries; drinking water; filtration; pot; silver

Introduction
The World Health Organization and UNICEF (2000) assessed that 1.1 billion people do not have access to “improved drinking-water sources”. The ambitious target established in the "Millennium Development Goals" (MDG # 7) is “halving the proportion of people without sustainable access to safe water and basic sanitation by 2015” (UN, 2006). According to the WHO, a short-term solution to meet the basic need of safe drinking water can be found in household water treatment and safe storage (WHO, 2002). Treating the raw water in the home diminishes the risk of recontamination during distribution, and the need for community-scale organisations is limited. Numerous household water treatment systems are designed for households in developing countries, using solar disinfection, sand and ceramic filtration. A design of a ceramic filter system is the Ceramic Silver-impregnated pot Filter (CSF). CSF (Figure 1) is manufactured with local materials and skills and is therefore an inexpensive product ranging from US$5 to US$12. A mixture of clay, sawdust and water is pressed into a pot shape with press
moulds. Once the filter element has its shape, it is fired in an oven and the sawdust is combusted to leave porous material. The filter element is impregnated with a mixture of colloidal silver, for assumed disinfection purposes, before distribution to the consumers.

The material properties of the filter element are not really known, but the manufacturers claim to aim for the filter element to have a maximum pore size of 1 μm. Previous research by Lantagne (2001) gives an indication of the pores sizes, with pores up to 500 μm in length (scanning electron microscope). The question remains if the pores measured in that specific material sample are representative for the filter element, and whether these pores influence the removal efficiency of pathogenic microorganisms. Although the system is widely used, knowledge of the material microstructure, removal of pathogens and other aspects such as the possible leaching of metals is limited. However, a scientific basis is needed for organisations to safely scale-up and implement the CSF system worldwide. The objective of this research study is to provide reliable performance data of CSF for drinking water treatment in developing countries. The study is divided into two sections.

1. Characterisation of the microstructure of the filter material with mercury intrusion porosimetry and bubble-point tests.
2. A long-term performance study of 12 weeks in the laboratory to monitor: (i) the removal efficiency of indicators for pathogenic microorganisms, (ii) leaching and/or retention of (heavy) metals, (iii) removal of turbidity, and (iv) filter discharge.

**Materials and methods**

**Characterisation of the filter material**

*Mercury intrusion porosimetry.* A mercury intrusion porosimeter was used to acquire specific information on the pore size in the filter material (Webb, 2001). To measure the pore diameters it is necessary to work with a non-wetting fluid, because a wetting fluid, like water, would enter the pores without applying pressure. Washburn (1921) first suggested the measurement of pore size distributions by the use of mercury injection. In a porosimeter the air is first evacuated from the sample container to remove contaminant gases and vapours (usually water), and subsequently mercury is allowed to enter. Next, pressure is increased and the volume of mercury entering the pores is monitored. The pressure is gradually increased to the maximum pressure of, in the case of the used instrument (Micrometrics Mercury Intrusion Autopore IV Series), 210 MPa to fill pores as small as 0.006 μm. Assuming cylindrical pores and circular pore openings, the relationship between applied pressure and the pore size diameter can be calculated (Webb, 2001). The measurements of a series of applied pressures and the cumulative

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**Figure 1** CSF system (source: Potters for Peace)
volumes of intruded mercury results in an intrusion curve. From this intrusion curve multiple material characteristics can be derived, such as pore size distribution, total pore area, porosity, permeability and tortuosity.

**Bubble-point test.** The water travels through many paths in the filter and the pore sizes along these paths determine which particles are retained in the filter. The smallest diameter determines what the largest passing particle is, also called the “effective diameter”. A bubble-point test was performed to determine the size of the largest effective pore of the filter. The bubble-point test is based on the fact that, for a given fluid and pore size with a constant wetting, the pressure required to force an air bubble through the pore is inversely proportional to the size of the hole. In practice this means that the largest effective pore size of the filter can be determined by forcing air through the pores. By gradually increasing the pressure in the filter element, the air is pushed through the pores. At a certain pressure a steady stream of air bubbles will escape from the filter, a condition called the bubble-point. It is possible to calculate the size of the effective pore diameter from the measured air pressure at bubble-point. To successfully perform the bubble-point test it is crucial that the filter be completely wetted and well sealed.

**Performance study**

Twenty-four filters were selected from three production locations for the long-term performance study, as shown in Table 1. The filters are normally impregnated with colloidal silver, but filters without impregnation from Nicaragua are also included in this study.

The filters were loaded daily with raw water from the canal Schie, a water body passing the city of Delft. The initial plan was to load the filters daily with this water to simulate the demand of a family. Unfortunately, as a result of widely varying filter discharges, in practice it was not possible to load all filters equally and fill all filters completely at least once a day. Therefore the daily load was set at 6 L day$^{-1}$ which would provide sufficient drinking water for two people only. The raw water was automatically applied to the filters and the filtrate was discharged into a sewer. Every week the influent and effluent water was tested for turbidity (Hach 2100N Turbidmeter), pH (WTW pH Electrode SenTix 41-3), temperature and conductivity (WTW TetraCon 325). For these parameters the raw water quality were, on average, pH 7.6, temperature 21°C and conductivity 1,050 $\mu$S cm$^{-1}$. The turbidity varied in the canal water between 0.8 and 31 NTU. During the performance study the filter discharge was measured weekly for a period of 1 h with a water level of 20 cm, at which the filter element is almost completely filled. A broad range of (heavy) metals was measured weekly in this study and analysed using ICP-MS (NEN-EN-ISO 17294-2).

An efficient removal of pathogenic microorganisms from raw water is one of the main tasks of ceramic silver-impregnated pot filters, and thus the main focus of this study. Detecting pathogenic microorganisms is complex and potentially hazardous, therefore the use of “indicator” organisms is introduced. Indicator organisms were measured in the influent

<table>
<thead>
<tr>
<th>Production location</th>
<th>Type of filter</th>
<th>Number of filters</th>
</tr>
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<tbody>
<tr>
<td>Cambodia</td>
<td>Standard, with silver</td>
<td>6</td>
</tr>
<tr>
<td>Ghana</td>
<td>Standard, with silver</td>
<td>6</td>
</tr>
<tr>
<td>Nicaragua</td>
<td>Standard, with silver</td>
<td>6</td>
</tr>
<tr>
<td>Nicaragua</td>
<td>No impregnation of silver</td>
<td>6</td>
</tr>
</tbody>
</table>
and in the produced water to determine the removal efficiency of the filters. The canal water naturally contained total coliforms and *E. coli*, indicators for pathogenic bacteria. Furthermore, indicator organisms were spiked to simulate high concentrations of contamination: *E. coli* K12 (10^5–10^7 cfu 100 mL^-1) as an indicator for pathogenic bacteria, sulphite reducing *Clostridium* spores (10^3–10^5 n 100 mL^-1) as an indicator for protozoa oocysts and MS2 bacteriophages (10^4–10^6 pfu mL^-1) as an indicator for pathogenic viruses. The analysis of total coliforms (NEN-EN-ISO 9308-1), *E. coli* (NEN 6571 and NEN 6570), *Clostridium* spores (NEN-ISO 6461-2), and MS2 bacteriophages (NEN-ISO 10705) were performed using standard procedures at certified Dutch drinking water laboratories.

### Results and discussion

#### Filter material characteristics

**Pore size distribution.** Mechanical screening is a process that involves removing particles of suspended matter that are too large to pass through the pores of the filter material. The pore size diameters in the filter material were measured to get an indication of the screening mechanism. In Figure 2 the percentage pore volume distribution by pore size is depicted for a sample of filter material per production location. It should be noted that the percentages on the vertical axis are calculated by multiplying the volume of intruded mercury per representative diameter by the density of the sample. Thus, the cumulative intrusion curves show the total porosity of the sample, which for all samples is between 34 and 43%. Despite some variations, the overall trend of the intrusion curves is similar, especially when taking into account that the filters are produced in different parts of the world, with different local materials and by different entrepreneurs. For all samples the majority of the pores are larger than the 1 μm claimed by the manufacturers. Of interest to the screening mechanism of the filter are the pores on the path followed by the water, because these pores contribute to the removal efficiency of CSF. The largest pores on these paths, the effective pores, were determined with the bubble-point test. The outcome of these measurements varies slightly per production location, with a mean of 40 μm and a standard deviation of 6 μm. These pores are again larger than 1 μm, and also larger than most pathogenic microorganisms. Mechanical screening is not the only filtration mechanism in CSF, thus these organisms may also be removed by mechanisms of adsorption, sedimentation, turbulence, diffusion and/or inertia.

**Figure 2** Mercury intrusion curves, both cumulative and incremental for the three production locations: Cambodia, Ghana and Nicaragua (van Halem, 2006)
Total pore area and tortuosity. Calculation of the total pore area and the tortuosity may contribute to understanding the filtration processes occurring in CSF. High pore surface areas contribute to the adsorption to the filter material. The pore areas were calculated from the mercury intrusion data and were 0.7, 1.3, and 1.2 m$^2$g$^{-1}$ for Cambodia, Ghana, and Nicaragua, respectively. The application of the silver impregnation showed a significant reduction in the pore area, because the filter material from a Nicaraguan filter without silver showed an average of 7.8 m$^2$g$^{-1}$.

The mercury intrusion and flow rate data also provided information on the tortuosity of the filter material. The tortuosity is a term to account for the non-direct route through the microscopic pores within the filter material, i.e. the ratio of the actual distance a particle must travel through the filter divided by the thickness of the filter wall. The measurements in this study showed that the material of CSF is very tortuous, for example compared to a sand filter. The effect of the total pore area and tortuosity on the removal efficiency of indicator organisms will be discussed later in this paper.

Performance study

Removal efficiency of total coliforms and E. coli. Total coliforms were naturally present in the Schie canal water at varying concentrations, 7–2100 cfu 300 mL$^{-1}$. During the long-term study, 144 effluent samples were taken and coliforms were detected in only 7% of these samples. In none of the samples was a concentration above 10 cfu 300 mL$^{-1}$ measured. Per week, the number of filters that produced water with no coliforms in the 300 mL sample was between 83–100%. It should be noted that the filters from Nicaragua without colloidal silver are not included in this overview. The measurements show some variation throughout the weeks, but a clear-cut relation cannot be found. During the long-term study the removal efficiency of coliforms was consistent, both in the filters with and without silver. The log(10) reduction values reached with this experiment varied between 1 and 4 log, depending on the influent concentration. Based on these measurements, it may be stated that microorganisms are not solely removed by mechanical screening in CSF. Other filtration mechanisms contribute to the efficient removal of total coliforms from the canal water, most likely caused by the tortuous nature of the filter material.

Surface waters in developing countries are often more polluted than the Schie canal water due to various activities along the river, such as washing and bathing. High concentrations of E. coli K12 (10$^5$–10$^7$ cfu 100 mL$^{-1}$) were therefore spiked to simulate these extremely contaminated waters. The mean log(10) reduction values (Figure 3) indicate that the removal of E. coli is very good in filters from all production locations. The Nicaraguan filters (with silver) reached, in almost all samples, the WHO guideline (WHO, 2006) that no coliforms may be detected in any 100 mL sample. The water of the filters from Ghana and Cambodia did not meet this guideline, but the log removal of these filters is still high. Filters manufactured in Nicaragua without the application of silver show the highest concentrations of E. coli. Concentrations between 10 and 29,000 cfu 100 mL$^{-1}$ were detected in these filters. However, again it must be noted that due to the extremely high influent concentrations, the log(10) reduction values are still very high for these filters. Thus, the conclusion that impregnation of colloidal silver is needed in CSF to remove significant concentrations of E. coli is not substantiated.

Removal efficiency of sulphite reducing clostridium spores. Sulphite reducing Clostridium spores were spiked to simulate the removal of pathogenic protozoa oocysts. The concentrations that were dosed varied per experiment between 10$^3$ and 10$^5$ n 100 mL$^{-1}$. Figure 4 depicts the mean, minimum and maximum log(10) reduction values per production location. The measured concentrations in the produced water were
consistent for all filters, thus the variation in the log(10) reduction values is caused by the varying influent concentration. From the results in Figure 4, it can be concluded that filters from all locations may be considered effective in removing indicators for protozoa oocysts. It also shows that the filters from Nicaragua perform best, regardless of the addition of a silver coating. This clearly indicates that colloidal silver in CSF is not needed to efficiently remove Clostridium spores from the water. These results for the efficient removal of Clostridium spores are consistent with the complete removal of turbidity from the raw canal water (below 0.25 NTU) by CSF.

Removal efficiency of MS2 bacteriophages. Previous research (Brown and Sobsey, 2004) has shown that adding colloidal silver onto the filter material surface possibly has a positive effect on the removal of bacteriophages. Partially based on this study, it was decided to spike MS2 bacteriophages twice during the long-term study, in the 5th and
13th week. The mean log(10) reduction value per production location are depicted in Figure 5. Remarkably, the log(10) reduction values of the filters from Nicaragua without colloidal silver is consistently higher than the filters with silver. The explanation for this might be that the application of colloidal silver reduced the (adsorptive) surface area of the filter material. Secondly, it is interesting to note that the log(10) reduction value is substantially increased by the 13th week of use. This could be due to smaller pores and the formation of a biofilm, which promotes adsorption and biodegradation.

Leaching of metallic compounds. Most chemicals in drinking water are of health concern only after extended exposure of years, rather than months (WHO, 2006). A broad range of metallic compounds were measured during the long-term study. Many metals were leached from the filter material, especially in the first few weeks; aluminium, antimony, arsenic, barium, copper, manganese, silicon and silver. For most compounds the effluent measurements decreased exponentially to concentrations far below the WHO guidelines. Arsenic, however, was the only compound found to leach in concentrations above the 10\( \mu \text{gL}^{-1} \) WHO guideline (2006). It is widely recognised that arsenic may cause cancer of the skin, lungs, urinary bladder and kidneys. Even though the concentrations reduced exponentially over time, the measured arsenic levels for the Cambodian filters in week 12 were still between 12–20\( \mu \text{gL}^{-1} \). This shows that filter material should be tested for the leaching of arsenic, especially in regions where high arsenic concentrations are known to be present in the soil.

A silver coating is artificially applied to the filters because it is believed to have a disinfecting function in CSF. However, ingestion of high silver concentrations can cause argyria, a condition in which skin and hair are heavily discolored by silver in the tissues (WHO, 2006). This permanent cosmetic condition is undesirable to consumers, but the measurements show lower concentrations in all filters than the 100\( \mu \text{gL}^{-1} \) WHO guideline.

Filter discharge. At the production location the clean water flux is measured as a quality check. Filters with a flux outside the range of 1–2Lh\(^{-1}\) are discarded, others are impregnated with silver and sold to consumers. Laboratory measurements have shown that the clean water flux increases within the first 24h of usage. Therefore, the filters are...
immersed and wetted before determining the flux. All purchased filters in this study must have passed this test, and thus should have clean water fluxes between 1 and 2 L h$^{-1}$. However, the clean water flux of most filters from Cambodia and Nicaragua were much lower than the 1 L h$^{-1}$ boundary. Some of the filters manufactured in Ghana had fluxes higher than the 2 L h$^{-1}$ boundary. The low fluxes are particularly worrying, because these fluxes are lowered further due to clogging in the course of time. The filter discharges were monitored over a period of 12 weeks, while being loaded with canal water (Figure 6). The turbidity in the raw canal water is very well removed by CSF, resulting in clogging of the filter material. As expected, the water production decreases over time. It is noteworthy that the filters without silver do not show different discharge reductions compared to filters with a silver coating.

Two high peaks were measured after cleaning/scrubbing the inside of the filter element according to the manufacturer’s manual. These discharge increments were, however, temporary with an overall decrease in water production clearly shown. Although the scrubbing procedure seems to have a positive effect, it does not stop the effect of long-term clogging. These low discharges are worrying because a reliable (household) water treatment system should not only produce safe water, but also sufficient water.

Conclusions
Although the effective pores (40 $\mu$m) exceed the size of most pathogenic protozoa and bacteria, the removal of *E. coli* and sulphite reducing *Clostridium* spores by CSF is very good. It may therefore be concluded that filter mechanisms other than mechanical screening are responsible for high log(10) removal values. This conclusion illustrates the importance of the high tortuosities measured in the filter material, i.e. a higher chance of adsorption, diffusion and sedimentation.

The role of colloidal silver in CSF is not completely understood. However, it is shown that colloidal silver is unnecessary for the efficient removal of *Clostridium* spores. The removal of *E. coli* proved to be better by filters with a layer of silver, but it is noteworthy that those filters without silver also reached high log(10) reduction values. MS2 bacteriophages were only partially removed by CSF, but were significantly better by filters without the silver impregnation. This is in contrast with previously reported studies.

Of all measured metallic compounds, only arsenic was found to leach from some of the filter material in potentially problematic concentrations. It is therefore recommended that the filter material undergoes a leaching test, especially in arsenic-rich regions.
This study also showed that – in the long run – the main deficiency of CSF is the insufficient water production to supply drinking water to a family. Future studies are needed to completely understand the mechanisms of clogging, but this study has shown that with the current cleaning procedure CSF is not a sustainable drinking water treatment system. Furthermore, we recommend the start of a certification procedure to improve standardization of the production methods for CSF.

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