Rapid sand filtration of *Cryptosporidium parvum*: effects of media depth and coagulation

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**ABSTRACT**

Pilot-scale experiments were conducted to investigate the removal of *C. parvum* by contact granular filtration. The experiments indicated efficient transport of *C. parvum* oocysts and limitations posed by attachment conditions. The required 99% oocyst removal was achieved during the operable period. Insufficient 95% removal was attributed to a reduced amount of accumulated material at ripening stage. Coagulation, filter depth and run time were found to be important in the removal of *C. parvum* oocysts.

**Key words** | Alum, deep-bed filtration, oocyst, sand filter

**INTRODUCTION**

Drinking water contamination is one of the most important environmental concerns necessitating worldwide attention. One of the greatest health risk management challenges for drinking water supplies is posed by disease-causing microbial contaminants, such as *Cryptosporidium parvum* (*C. parvum*). Penetration of oocysts of *C. parvum* through water treatment systems caused numerous outbreaks of cryptosporidiosis—a disease with no therapeutic care, potentially lethal for people with a depressed immune system and AIDS sufferers. Unlike other microorganisms, *C. parvum* oocysts are unusually resistant to traditional disinfectants such as chlorine and chloramines (*Finch et al. 1993*). As a result, water utilities are showing increased interest in oocyst removal by granular porous media, using approaches such as deep-bed (granular) filtration, riverbank filtration and slow-sand filtration (*Timms et al. 1995; Huck et al. 2002; Tufenkji et al. 2004*).

Intensive research, initiated since the first *C. parvum* outbreaks, found a safe level of more than 99% oocyst removal during the optimal operable stage of the filtration cycle (*Swertfeger et al. 1999; Lipp & Baldauf 2000*). Both conventional (coagulation, flocculation, sedimentation and filtration) and direct (coagulation, flocculation and filtration) filtration schemes were monitored. A proper coagulation/flocculation regime was recognised as the single most important step in *C. parvum* removal (*Edzwald & Kelley 1998*). Later studies on the influence of solution chemistry, fluid flow rate and media grain size (*Logan et al. 2001; Tufenkji et al. 2004; Abudalo et al. 2005; Bradford & Bettahar 2005; Emelko et al. 2005; Tufenkji & Elimelech 2005*) emphasised the need to better understand the effects of various operating conditions on the removal of oocysts in different treatment schemes. All the studies indicate that rapid granular filtration, when operated under appropriate coagulation conditions and optimised to achieve a filtered water turbidity level of less than 0.3 NTU, should reduce the effluent concentration of *C. parvum* oocysts by at least 99%. However, in a nationwide study, *Rose (1997)* observed the oocysts in as much as 28% of treated drinking water samples. The series of cryptosporidiosis-related incidents worldwide, their regulatory aftermaths and their economic consequences, have seriously challenged the faith the water practitioners have in the granular filtration technologies. In spite of the recent upsurge in related research projects in both the laboratory and the field, the manner in which the oocysts interact with flocs and flocculants and filter media remains largely unknown.

The reported study was initiated by US EPA to reassess factors that influence the retention of *C. parvum* oocysts by rapid sand filtration. Despite an intensive use of membrane technologies, many municipal potable water treatment plants around the world are still using granular bed filtration as a robust, simple and inexpensive method to prevent penetration of disinfectant-resistant pathogenic microorganisms. For those plants, the influence of operation parameters such as proper coagulation and filter depth, is reported.

**METHODS**

The filtration system and detailed experimental procedure were described previously (Gitis *et al.* 2002a, 2005). Briefly, the influent suspension was mixed in tap water inside a 1,000 L Cross-Linked Polyethylene (XLPE)-made feed water supply tank by a high-speed mixer (model VL3501, Baldor Electric Co., Fort Smith, AR). A centrifugal pump (model AC-3C-MD, March Manufacturing Inc., Glenview, IL) was used to lift the suspension into a 100 L head tank located 3.6 m above the filtration column. The water level in the feed tank was maintained at a constant height by an overflow line returning the suspension to the feed tank. A 17 cm diameter, 2.6-m high acrylic transparent filter column was used for the study. The column was packed with 1.6 m of uniform size sand having a geometric mean diameter of 1.05 mm and a uniformity coefficient of 1.55 (#5 Silica Torpedo Sand, Parry Company, Richmond Dale, OH). Nine sampling and nine pressure ports were located in pairs on opposite sides of the column. The height of the sampling ports throughout the paper is indicated from the sand upper level. The media porosity, determined by volumetric measurements, was 0.44. The column was operated at a constant flow rate under contact (coagulation–filtration) mode in a conventional downward direction. The filtration velocity was controlled and adjusted by a flowmeter (model U-32470-02, Cole-Parmer Instrument Co.) connected to the column outlet. If not specified otherwise, the experiments were performed with $u = 10 \text{ m/h}$ approach velocity. Immediately after each run, the filter was backwashed for 1 min by air at 200 kN/m$^2$ pressure, followed by 10 min upflow of tap water at 1.1 L/s. Both caused 50% bed expansion. To avoid risk of cross-contamination, the filter was chlorinated and all removable parts of the system (pumps, baths, pipes) were sterilised after each run. The influent was prepared on site by addition of 10 mg kaolin (Sigma-Aldrich) and 8·10$^6$ oocysts of *C. parvum* per 1 L of tap water. Turbidity was measured on site using a 2100P turbidimeter (Hach Company, Loveland, CO). Enumeration of *C. parvum* oocysts was performed using Immuno Fluorescent Assay (IFA) technique, following the procedure described by Kao & Ungar (1994). Coagulation was performed with alum [Al$_2$(SO$_4$)$_3$·18H$_2$O] (Sigma-Aldrich Inc.) solution, injected into the raw suspension using a peristaltic pump (model Masterflex P-07553-70, Cole-Parmer Instrument Co., Vernon Hills, IL). Injection of alum was performed 30 cm above static mixer (Gitis *et al.* 2005). The latter was connected 0.5 m above the entrance to the filtration column. The optimal dose of alum was found using a series of flocculation/sedimentation tests (jar-tests). Addition of alum was performed at the pH values of tap water. Optimisation of pH was beyond the scope of the reported research.

**RESULTS AND DISCUSSION**

Figure 1 depicts oocyst removal ratio as a function of filtrate volume through the bed, in the presence and absence of alum. *C. parvum* removal ratio was defined for oocyst counts at 0.4 m filter depth and for 2 cm above filter media. A concentration of 20 mg/l alum was the optimal dose for filtration based on jar-test experiments and previous
recommendations (Adin et al. 1979). Filtration experiments performed with no chemical destabilisation resulted in poor removal of the oocysts. Unstable filtrate quality, influenced by hydrodynamic conditions, was constantly more pronounced for small depths (data not shown) and became moderate as the filter became deeper. The addition of an optimal 20 mg/l dose of alum improved the quality of filtrate, and resulted in oocyst’s surface charge neutralisation. Performed calculations of compensating depth of electrical double layer suggested that at a distance of 3–4 nm from the C. parvum surface, the electric potential $\psi(r)$ dropped to approximately zero levels. Calculations of the depth of the electrical double layer for experiments performed with no alum addition showed values of 20–23 nm. Performed zeta-potential measurements confirmed theoretical calculations and showed values closed to electro-neutrality ($-1.26$ mV) for experiments performed with alum addition.

The experiment was repeated with 20 mg/l alum to assess the influence of coagulation on the residence time. We intuitively tend to calculate the residence time of microorganisms inside the media by hydraulic means, simply dividing filter depth by approach velocity. That might not necessarily be true (Gitis et al. 2002b) and, depending on the filtration stage, microorganisms might remain inside the filter for longer periods of time. The oocyst spikes were performed at four filter run times and after each spike at each monitored port, effluent samples were collected into three 20 L jars. The concentration of C. parvum oocysts in each jar was detected separately so for each spike at each monitored depth (10, 40 and 80 cm) three various concentrations were obtained. To achieve a detectable oocyst level, each jar was filled for 10 min. The collection of the first jar started 8 min after the spike, and that “dead” time was calculated as a path length between injection and collection points, divided by filtration velocity.

The obtained results are shown in Figure 2 and Table 1. Figure 2 shows residual concentrations in each jar at 40 cm filter depth for spikes performed at 0, 60, 180 and 360 min filter run. The results obtained for other filter depths along with calculation of mean residence time and its variance are presented in Table 1. The residence time and its variance were calculated by

\[
\bar{t} = \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i},
\]

\[
\sigma^2 = \frac{\sum t_i^2 C_i \Delta t_i}{\sum C_i \Delta t_i} - \bar{t}^2
\]

Here, $\bar{t}$ is the average retention time; $t$ is the time after injection $i$; $C_i$ is crypto concentration; and $\sigma^2$ is the retention time variance.

The concentration of oocysts in the first jar collected at the beginning of the filter run was higher than the concentration in the second and third jars, and therefore the mean residence time of 17.7 minutes was found. However, at the run times of 60 and 180 min the concentration of oocysts in three jars was approximately equal and therefore the residence time increased up to 20 and 21 minutes. After six hours of filter run the concentration in the third jar was higher than in two others and the mean residence time increased up to 26 min. A similar tendency was observed at 80 cm filter depth. Here, means residence time increased from 25 to 29 minutes, while for experiments performed at 10 cm filter depth no changes in residence time was observed. The observed tendency suggests that interactions of media grain with oocysts, and diffusion of the latter to the grains and back, sufficiently increase residence time. For deep filters the pathogen residence time is much higher than it can be approximated by hydraulic calculations. The calculated axial dispersion coefficient D showed growing values of $1.2 \times 10^{-4}$ to $7.6 \times 10^{-4}$ m$^2$/s, pointing on increased axial diffusion of oocysts as the filter run progresses.
Growing dynamics of average retention time indicates a shift from interactions of *C. parvum* particles with media grains to interaction with kaolin particles coated the media. When the media grains are essentially free of deposit, *C. parvum* oocysts either accumulate on media grains or pass through the filter bed. Kaolin particles present better accumulation opportunities from both electrostatic and hydrodynamic points of view. The number of interactions is growing and causes an increase in average retention time, along with a constant increase in removal efficiency.

Figure 3 depicts log removal, calculated on turbidity and oocyst basis, as a function of run time. The log removal was defined as $\log_{10}(C_0/C)$ and was calculated from the actual measured influent value and the actual effluent value or detection limit, 0.05 oocyst/ml, when no oocysts were found.

In all three depths turbidity removal efficiency was larger at the beginning of the run, 0.2, 0.7 and 1.2 logs removal at 10, 40 and 80 cm filter depth, respectively. The initial high removal can be attributed to dilution of the suspension with clean water that remained in the filter after backwash. The removal efficiencies decreased after 1 hour of filter run, and reached a plateau an hour later. At the same time, removal of *C. parvum* (Figure 3b) constantly improved for each port as filter run progressed. For 10 cm depth, removal efficiency reached 0.5 log at the beginning of

### Table 1

<table>
<thead>
<tr>
<th>Run time (min)</th>
<th>Filter depth (cm)</th>
<th>10</th>
<th>40</th>
<th>80</th>
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<tbody>
<tr>
<td></td>
<td>C (#/ml)</td>
<td>t (min)</td>
<td>$\sigma^2$</td>
<td>C (#/ml)</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>1297</td>
<td>2186</td>
<td>17.4</td>
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<td>68.3</td>
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<tr>
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<td>12.5</td>
<td>21.9</td>
<td>0.5</td>
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<tr>
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<td>221</td>
<td>18.8</td>
<td>43.9</td>
<td>18</td>
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<td>17.3</td>
<td>47.1</td>
<td>6.7</td>
</tr>
<tr>
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<td>17.3</td>
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</tr>
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<td>54</td>
<td>2.3</td>
<td>2.5</td>
<td>1.1</td>
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</tr>
</tbody>
</table>

Statistical analysis of the obtained data was performed with more than 450 discrete filter efficiency data points acquired with three flow velocities, three flocculant concentrations, five sampling depths, and ten sampling times. Two five-way analysis of variance (ANOVA) was conducted to investigate the effect of those independent variables on turbidity and oocyst removal ratios. The significance of the main effects alone was investigated: all interactions were found to be not statistically significant and were pooled with the error. The omnibus F-ratio was highly statistically significant for both turbidity and oocyst ratio, indicating that there are sources of variability in either model that cannot be attributed to chance alone (Winer et al. 1997). Indeed, as described previously, the sample depth was found to be statistically significant for both ratios ($p$-value < 0.0001). In addition, the flocculant concentration was found to significantly affect the oocyst ratio ($p$-value < 0.0001), but not the turbidity ratio. Flow velocity was not a significant factor for both ratios. Yielded conclusions were supported by Student-Newman-Keuls (SNK) multiple comparison tests.
Figure 4 depicts the effect of run time on the minimum protection filter depth, calculated to obtain the 2-log reduction of initial oocyst concentration required by Long Term 1 Enhanced Surface Water Treatment and Filter Backwash Rule (US EPA 2003). The reduction was achievable only with the application of an optimal chemical regime. Crypto removal remained below the required reduction level for experiments carried out without flocculants, as well as for the experiment performed with flocculant dosage below the optimal level. The addition of an optimal dose significantly improved total retention to average more than 3 logs (99.9%). The minimum protection depth decreased repeatedly as the run progressed. The depth was found to be lower for 10 m/h (curve 4) than for 5 m/h (curve 1). Unexpectedly, the addition of kaolin did not decrease the minimum protection depth (curve 3 vs. 4). The presence of organic material (curve 2) increased the minimum protection depth compared to the experiment performed without natural organic matter (NOM, curve 1). This is due to increased colloidal stability caused by electrostatic stabilisation. Dissolved humic substances adsorb on mineral surfaces (Petrovic et al. 1999), cause charge revolution of positively charged mineral edges (Brady et al. 1996) and increase negative surface charge. A higher filtration rate increases C. parvum adsorption. Experiments performed at 5, 10 and 17 m/h approach velocity showed a higher degree of C. parvum removal with higher velocity (data not shown). The effect was attributed to the amount of inorganic particles accumulated on the media grain surface. Higher filtration velocity contributed to larger kaolin accumulation, and a formed kaolin bed on media grain adsorbed better than the grain itself. The hypothesis was tested by simultaneous correlation analysis using sets of data for oocyst and turbidity removal. Pearson’s $R^2$ correlation coefficient was 0.52, suggesting that under the conditions tested, enhanced C. parvum removal can be linked to the amount of deposited kaolin. However, the absence of solid correlation indicates that low values of turbidity may cause a misinterpretation of the risk of microbiological contamination.

**CONCLUSIONS**

The removal of C. parvum using the contact filtration scheme was affected by three factors—run time, coagulant or flocculant addition, and filter depth. The best oocyst removal was found at an operable stage using the correct...
chemical regime on deep filters. However, in non-optimised conditions optimal values of two out of three factors will reduce the risk to public health posed by *C. parvum*.

This study indicates that rapid contact granular filtration can provide satisfactory levels of reduction in *C. parvum* concentrations. In highly turbid water, an average reduction of 3 logs concentration of *C. parvum* oocysts was found during the operable stage. Insufficient levels of 1.7 logs during the ripening period were linked to a reduced amount of accumulated material. Higher effluent concentrations of oocysts were observed during the period of poor coagulation/flocculation regime.

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**REFERENCES**


