Control of biofilm growth in drinking water distribution system by biodegradable carbon and disinfectant residuals

X.-J. Zhang and W. Lu

Department of Environmental Science and Engineering, Tsinghua University, Beijing 100084, China
(E-mail: *zhangxj@tsinghua.edu.cn*; *luw02@mails.tsinghua.edu.cn*)

Abstract Biofilm growth in drinking water distribution systems was studied in an annular reactor system which was designed to model the hydraulic conditions in water mains. Experiments were performed with chlorine-free water as well as with different disinfectant (chlorine or chloramine) residuals and different AOC concentrations added to the reactor influent to examine the effect of disinfectant residuals and AOC concentrations on biofilm accumulation and planktonic cell numbers. The dynamic parameters of bacteria growth were calculated in water with different disinfectant (chlorine or chloramine) and the results indicated that monochloramine may be more effective than free chlorine for control of biofilm accumulation.
Keywords AOC; biofilm; chloramine; chlorine; drinking water; dynamics

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Introduction

It is becoming obvious that biofilm on distribution pipes is one of the main factors affecting bacteriological quality of drinking water and disinfectant decay in distribution systems. The traditional method for controlling bacterial growth in distribution systems is the application of disinfectants, but with the increasing of disinfectant residuals, disinfectant by-products could be another problem. To limit the accumulation of bacteria in drinking water and the formation of biofilm in distribution systems, two parameters should be taken into account: the disinfectant residuals and the nutrients.

To control bacterial regrowth without increasing the dependence on disinfection, removing nutrients during water treatment processes is important. Therefore, to determine which of the nutrients, organic carbon, nitrogen or phosphate is limiting to biofilm development is the first step. Since carbon is needed the most for bacterial growth, it is often considered as the limiting factor in drinking waters. Some studies have shown a positive relationship between the concentration of biodegradable organic matter in drinking water and bacterial regrowth in distribution systems (van der Kooij, 1992; Owen *et al.*, 1995). More recently, however, phosphorus, as phosphate, has been found to be limiting in certain water types (Miettinen *et al.*, 1997; Sathasivan and Ohgaki, 1999).

Chlorine and monochloramine are used extensively in the disinfection of drinking waters to reduce the problem of bacterial regrowth in distribution systems. Chlorine reacts readily with organic carbon and pipe materials thus creating difficulties in maintaining chlorine residuals throughout distribution systems. The loss in disinfectant residual generally leads to an increase in disinfectant application. Obviously, the outcomes are the increased operating costs and disinfection by-product formation. Monochloramine has many advantages over chlorine. Monochloramine does not react with organic matter to the same extent as chlorine (LeChevallier *et al.*, 1988a) but has a greater penetration of biofilms (LeChevallier *et al.*, 1988b). As monochloramine is less reactive, the formation of disinfection by-products is also reduced. A disadvantage of

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monochloramine, however, is that longer contact times or higher concentrations are needed to obtain similar results to those achieved with chlorine.

There is a paucity of data on the growth dynamic parameters of biofilms and planktonic bacteria in drinking water. The aims of this research were to use annular reactors, under controlled laboratory conditions, to determine the effectiveness of two commonly used disinfectants to control biofilm development and the dynamic parameters.

Materials and methods

Water sources

Experimental water was obtained from the laboratory tap in Department of Environmental Science and Engineering, Tsinghua University, China. The water source is groundwater and because of the excellent water quality, the water does not need any treatment and is transported to the users directly. The normal water quality data are listed in Table 1.

Annular reactor operation

Biofilms were formed on the surface of polycarbonate slides ($23 \times 100\,mm^2$) in annular reactors, under continuous flow conditions. Biofilms were allowed to form for 12 days at 15 °C to pseudo-steady state. Biodegradable carbon (acetate carbon) and disinfectant (free chlorine and monochloramine) were added to the inlet of the reactor. Water residence time was set as 35 minutes to control the growth of planktonic cells.

Planktonic phase quantitation

Aliquots (10 mL) of the aqueous phase were aseptically removed to prepare a dilution series with sterile distilled water of which 0.1 mL samples were plated onto minimal R2A agar and incubated at 30 °C for 2–5 days.

Biofilm analysis

Attached bacteria were released from coupons by 2 minutes, sonication in 20 mL sterile MilliQ water. Heterotrophic bacteria were enumerated by the standard spread plate proceduree using R2A agar, incubated at 22 °C for 7 days. Analyses were carried out in triplicate.

Results and discussion

To evaluate the impact of disinfection processes and biodegradable carbon concentration on biofilm formation, different disinfectants were applied with doses similar to those used in practise. In Chinese National Health Regulation, chlorine residual should be at least 0.3 mg/L for free chlorine and 0.5 mg/L for monochloramine in the outlet of drinking water treatment plant. And the chlorine residual should be at least 0.05 mg/L at the end of the pipeline. Thus, in this study, the chlorine residual in the annular reactor was 0.05, 0.3, 0.5 and 1.0 mg/L. Biodegradable carbon concentration was evaluated by Assimilable Organic Carbon (AOC). AOC concentrations used in the study were: 50, 150, 350 and 500 μg/L.

Table 1 Quality parameters of experimental water

Parameter	Range
Temperature (°C)	6–11
pH	8.0–8.5
TOC (mg/L)	0.31–0.48
CODMn (mg/L)	0.54–0.78
Turbidity (NTU)	0.08–0.16

Chlorine and AOC

Biofilm formation on the coupons is shown in Figures 1 and 2. Within 8 days, biofilm formation arrive at the pseudo-steady state. All the attached bacteria counts were done on the 12th day. In Figure 1, the ability of attached bacteria to grow in the presence of disinfectant residual (0.05–0.5 mg/L) was demonstrated. AOC concentration had significant influence on the bacteria growth. The influence of 0.05 mg/L free chlorine residual on the attached bacteria counts was insignificant. When the chlorine residual was more than 1.0 mg/L, the growth of attached bacteria was controlled under the detection limit.

Monochloramine had a similiar effect on the growth of attached bacteria. To judge the difference of inactivation efficiency between free chlorine and monochloramine quantitatively, the dynamic process of bacteria growth should be analyzed and the dynamic parameters should first be determined.

Dynamic parameters

The net growth of free bacteria and attached bacteria, X_f and X_a, is given by the classic model:

$$\frac{dX_f}{dt} = (\mu_f - k_f)X_f \text{ and } \frac{dX_a}{dt} = (\mu_a - k_a)X_a$$

and

$$\mu_f = \mu_{fmax} \cdot \frac{S}{k_{fs} + S} \cdot \exp(-k_{cl1} \cdot [cl_2]); k_f = k_{fn} + k_{fin} \cdot [cl_2]$$

$$\mu_a = \mu_{amax} \cdot \frac{S}{k_{as} + S} \cdot \exp(-k_{cl2} \cdot [cl_2]); k_a = k_{an} + k_{ain} \cdot [cl_2]$$

In the annular reactor, when biofilm growth arrived at a pseudo-steady state:

$$\frac{\partial X_a}{\partial t} = (\mu_a - k_a) \cdot X_a - k_{bd} \cdot X_a + k_{fa} \cdot X_f \cdot R = 0$$

where k_{fa} is the first-order kinetic constant for free bacteria to deposit onto pipe wall and k_{bd} is the first-order kinetic constant for bacteria detachment.

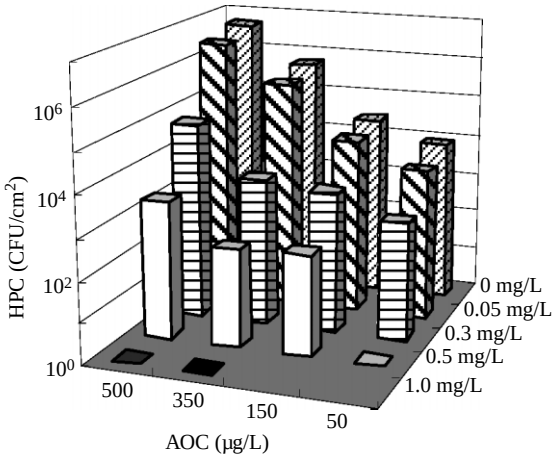

Figure 1 Effect of AOC and free chlorine residual on the growth of attached bacteria

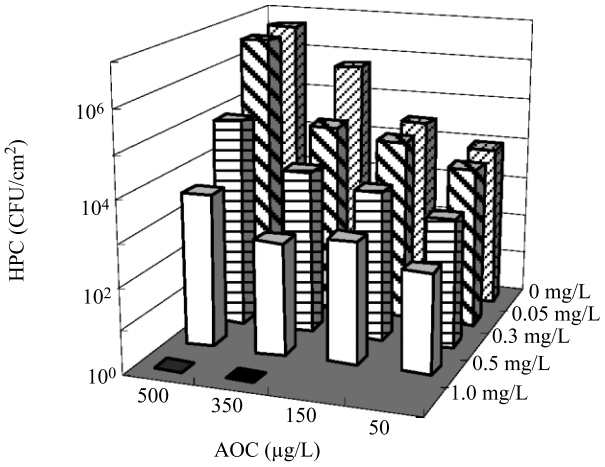

Figure 2 Effect of AOC and monochloramine residual on the growth of attached bacteria

Table 2 Dynamic parameters of bacteria growth

Parameter	Symbol	Unit	Free chlorine	Monochloramine
Maximum growth rate of free bacteria	μ_{fmax}	h^{-1}	0.113	0.113
Maximum growth rate of attached bacteria	μ_{amax}	h^{-1}	0.113	0.113
Monod half saturation coefficient (free bacteria)	K_{fs}	$\mu g \cdot L^{-1}$	40	40
Monod half saturation coefficient (attached bacteria)	K_{as}			
Bacterial mortality rate (free bacteria)	k_{fn}	h^{-1}	0.0142	0.0142
Bacterial mortality rate (attached bacteria)	k_{an}			
Rate constant for inactivation of free bacteria by chlorine	k_{cl1}	$L \cdot mg^{-1}$	3.637	3.367
Rate constant for inactivation of attached bacteria by chlorine	k_{cl2}	$L \cdot mg^{-1}$	0.85	2.75
Chlorine-induced mortality rate constant of free bacteria	k_{fin}	$L \cdot mg^{-1} \cdot h^{-1}$	1.421	1.256
Chlorine-induced mortality rate constant of attached bacteria	k_{ain}	$L \cdot mg^{-1} \cdot h^{-1}$	0.046	0.117
First-order kinetic constant for detachment	k_{bd}	h^{-1}	0.0025	0.0025
First-order kinetic constant for deposition	k_{fa}	h^{-1}	0.25	0.25
Growth yield coefficient of bacteria	Y	$\mu g \cdot cell^{-1}$	9.0e + 7	9.0e + 7

All the symbols and the corresponding explanations are listed in Table 2. Dynamic parameters were fitted by non-linear least-squares programme. The data of free bacteria growth were collected by the laboratory test.

Table 2 demonstrates that the inactivation efficiency of free chlorine on the free bacteria was better than monochloramine, but monochloramine had a stronger effect on the growth of attached bacteria.

Conclusions

By the solution of dynamic parameters, the difference of inactivation efficiency between free chlorine and monochloramine was determined quantitatively. Monochloramine seems more effective on the inactivation of attached bacteria. 0.05–0.5 mg/L of monochlamine and free chlorine were not found to prevent the formation of biofilms.

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