Disinfection of purified sewage effluent with monochloramine

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Abstract

The inactivation of faecal coliforms in purified sewage effluent by monochloramine was investigated using batch tests. For comparative purposes the data obtained were fitted to various published disinfection models. The series-event kinetic model was found to be the most suitable and was used in conjunction with tracer experiments to compare the predicted and observed inactivation of faecal coliforms in two continuous-flow systems. The value for the apparent kinetic constant K, was found to vary between 0.23 and 2.18 min^{-1} for monochloramine concentrations in the 1 to 5 mg/ℓ range and pH values between 6 and 8. The model was able to predict the behaviour of the continuous-flow systems. A design example for the determination of the monochloramine concentration required for a specific inactivation of faecal coliforms in an existing contact tank is given.

Background

The South African General and Special Standards stipulate that treated sewage effluent should comply to a standard of nil faecal coliforms/100 mℓ (Act 96 of 18 May 1984 No. 9225, Regulation 991). This standard can only be achieved by disinfection. Various methods of disinfection are available including physical (e.g. ultraviolet radiation) (Carnimeo et al., 1994) and chemical processes (e.g. chlorine, bromine and ozone) (Aieta et al., 1980; Jacangelo et al., 1989). According to White (1992) the most prevalent practice of disinfection is free chlorine ($HOCl + OCl^-$). This is also the practice in South Africa as was confirmed by a recent survey (Unpublished data, Univ. of Pretoria, 1996). Chlorine is a very reactive chemical and does not only disinfect, but also rapidly reacts with contaminants such as NH_4^+, NO_2^-, H_2S, Fe^{++}, Mn^{++} and organic compounds (Yamamoto et al., 1988; Teefy and Singer, 1990). These compounds create a chlorine demand so that chlorine is applied until the demand is met and free chlorine appears. This practice is called breakpoint chlorination and is wasteful in that it consumes more chlorine than is required for disinfection alone. The reaction of free chlorine with certain organic compounds present in wastewater leads to the formation of a group of compounds called trihalomethanes (THMs) (Johnson and Jensen, 1986), which have associated health risks (Reynolds et al., 1989). This is a concern in South Africa where treated sewage effluent is often reused as drinking water.

Some of the problems associated with free chlorine can be overcome by using chloramines for disinfection. Benefits of using chloramines include a reduction in the formation of THMs as reported by Reynolds et al. (1989) and greater disinfectant stability resulting in a reduction in disinfectant demand. Disadvantages of chloramines are their relatively long lifetime (compared to free chlorine) after discharge to the receiving environment, possibly with toxicity problems (Yamamoto et al., 1988) and their detrimental effect on kidney dialysis patients (Kreft et al., 1985).

The chloramines are formed by the reaction of free chlorine with ammonia. The reaction produces three main compounds, monochloramine (NH_2Cl), dichloramine ($NHCl_2$) and trichloramine or nitrogen trichloride (NCl_3). Palin (1974) showed that the dominant species formed in the reaction is dependent on the chlorine to nitrogen mass ratio (Cl_2:N). A low ratio (up to 5:1) favours the formation of NH_2Cl and higher ratios (up to 7.6:1) favour the formation of $NHCl_2$ and NCl_3. Ward et al. (1984), found that the three species also vary in their disinfectant power, with monochloramine being less effective than dichloramine. Studies have shown that free chlorine is a more effective disinfectant than the chloramines (Berman et al., 1992; Kouame and Haas, 1991; Rice et al., 1993; Ward et al., 1984) while some field reports (that observe naturally occurring bacteria and water with a chlorine demand) have shown that chloramines are adequate, and in some cases superior to free chlorine in terms of indicator organism reductions (Dice, 1985; Shull, 1981; Reynolds et al., 1989; ASCE, 1986).

Disinfection with chlorine and chloramines is influenced by five major factors, i.e. initial indicator organism concentration, disinfectant concentration, contact time, temperature and pH. Batch inactivation studies, performed in the laboratory to observe the efficiency of a disinfectant, are usually performed with pure culture bacteria, distilled water and well defined contact times (Ward et al., 1984). This is not the case in practice, where a complex mixture of bacteria and chemical species is present, and the contact time is dependent on the mixing regime (Teefy and Singer, 1990). The design of a full-scale disinfection process would be enhanced if the results of batch inactivation studies performed on real sewage effluents in the laboratory could be matched with the hydraulic behaviour of a real continuous-flow contact chamber.

The aim of this work was to evaluate the disinfection efficacy of monochloramine under operational conditions and to show how this information may be used in the design calculations of a chloramine disinfection system.

Theoretical

Kinetic models for batch inactivation

Since the turn of the century various mathematical models have been developed to describe the inactivating action of a disinfectant on micro-organisms. The main inactivation models found in the

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TABLE 1
SUMMARY OF THE PRINCIPLE INACTIVATION MODELS

Model	Eq.	Author	Comments
$\ln\frac{N_t}{N_o} = -kC^n t$	(1)	Chick/Watson (1908)	First-order with respect to surviving bacteria if C is constant. k is the pseudo first-order reaction rate constant and n is the coefficient of dilution.
$\ln\frac{N_t}{N_o} = -kC^n t^m$	(2)	Hom (1972)	Model developed to account for deviations from the Chick-Watson model in practice. m is an empirical constant and k and n are as for Eq. (1).
$\ln\frac{N_t}{N_o} = -k' t^m$	(3)	Hom (1972)	Modification of Eq. (2) for constant disinfectant concentration. k' = kC^m in Eq. (2).
$\frac{N_t}{N_o} = e^{-kct}\sum_{i=0}^{j-1}\frac{(kct)^i}{i!}$	(4)	Severin et al. (1984)	The series event kinetic model where k is the mixed second-order reaction rate constant and j is an integer represent-ing the lethal number of reactions for a single organism. The term kC may be replaced by K, the apparent kinetic constant
$\ln\frac{N_t}{N_o} = -\left(\frac{m}{nk^*}\right)^m k(C_o)^n\left[1-\exp\left(-\frac{nk^*t}{m}\right)\right]^m$	(5)	Haas et al. (1998)	A modification of the Hom model developed to take residual disinfectant decay into account. k, m and n are the same as for Eq. (2). C_o is the initial disinfectant concentration and k* the first-order residual decay rate.

N_o = initial concentration of organisms; k = reaction rate constant; k^* = first-order residual decay rate
N_t = organism concentration at time t; m = empirical constant; j = lethal number of reactions
C = disinfectant concentration; n = coefficient of dilution

literature are summarised in Table 1.

Because the recent models (Eqs. (4) and (5)) are more complex than the older ones (Eqs. (1), (2) and (3)), all the models were compared to determine which one gave the best prediction of the kinetics for batch inactivation studies and to determine whether the more complex models are more accurate than the older models. The rationale was to identify a model that is both accurate and simple.

Continuous flow residence time distribution models

Not all the elements of a fluid pass through a reactor along the same flow path and some short-circuiting may take place. This creates a distribution in the residence time as shown by Levenspiel (1972: 255) of the different fluid elements, called the residence time distribution (RTD). Tracers are used to measure the RTD of a reactor. The tracer is injected at the influent to the reactor and measured as it exits. The resulting response curve may then by analysed by means of mathematical models. Three models are available for this analysis: the tanks-in-series model, the dispersion index model and indices calculated from single points on the response curve.

The tanks-in-series model assumes that the flow through a real reactor may be represented as though it flows through a series of equally sized completely stirred tank reactors (CSTRs) (Levenspiel, 1972: 290). The number of CSTRs, N, is obtained by comparing the tracer response curve of a reactor to the theoretical response of a known number of CSTRs. Values of N range between two theoretical extremes (Smith, 1981: 283), i.e. N = 1 (a completely mixed reactor) and N = ∞ (a plugflow reactor). One of the advantages of the tanks-in-series model is that it uses all measured data and not only single points on the response curve.

The tanks-in-series model is used to evaluate tracer data obtained in this study because mathematical models already exist that combine batch disinfection data with a tanks-in-series model as shown by Severin et al. (1984). To combine the residence time distribution of a continuous-flow system with the results of a batch inactivation study it is necessary to write the batch model as an inactivation equation that will predict the survival ratio (N_t/N_o) of the bacteria in the effluent stream. The inactivation equation developed by Severin et al. (1984): for the series-event model was used in this study and is given below :

$$\frac{N_t}{N_o} = \left(\frac{1}{1+K\tau'}\right)^N \cdot \sum_{i=0}^{j-1}\left[\frac{i+N-1}{N-1}\right]\left(\frac{K\tau'}{1+K\tau'}\right)^i \qquad (6)$$

where:

K = apparent kinetic constant (min^{-1})
τ' = residence time in one CSTR
N = number of equally sized CSTRs in series
N_o = initial concentration of organism
N_t = concentration of organism at time t (min).

The value of τ' and N can be obtained from tracer studies while the value of K and j can be obtained from batch inactivation experiments.

The experimental work done in this study can be summarised as follows:

- Batch inactivation experiments were conducted with treated sewage effluent to determine the effect of pH and monochloramine concentration on the inactivation rate of naturally occurring faecal coliforms in the effluent.
- Tracer studies were conducted on two continuous-flow laboratory-scale contact chambers, namely reactors in series and a channel-flow reactor, to determine their flow regimes (number of CSTRs in series, N).
- The data obtained in the batch inactivation experiments were fitted to mathematical models to identify the most accurate model.
- The data measured in the batch inactivation experiments and tracer experiments were combined (Eq. (6)) to predict the inactivation in the two continuous-flow systems.
- Inactivation was measured in the two continuous-flow systems and was compared to the predictions of Eq. (6).

Methodology

Test water

All the experiments were conducted on secondary treated effluent from a typical biological nutrient removal wastewater treatment plant, treating mainly domestic sewage. Samples of the effluent were collected from the secondary settling tank overflow (before disinfection) in batches and stored at 4°C within 1 h of collection. Experiments were done within 4 d after collection. Thereafter the samples were discarded and new samples were collected.

Preparation of disinfectant solution

Before each set of inactivation studies a fresh stock solution of monochloramine was prepared by adding 44 mℓ of a 5% (m/m) NaOCl solution (ACE chemicals) to 456 mℓ of a 8.3g/ℓ HH_4Cl solution (Merck) to produce 500 mℓ of a NH_2Cl concentration of ca. 2 g/ℓ (Cl_2:N mass ratio = 3:1)(Ward et al., 1984). The solution was stirred for 1 h to allow the reaction to go to completion and was standardised by analysing the different chloramine species using the ferrous ammonium sulfate-diethyl-*p*-phenylenediamine titrimetric method (*Standard Methods*, 1989).

Batch inactivation studies

To determine the effect of pH on disinfection efficiency , inactivation studies were conducted at pH 6, pH 7 and pH 8. The experiments were conducted in the monochloramine concentration range of 1 to 5 mg/ℓ as Cl_2 . The actual monochloramine concentration present in each individual experiment varied within this range and was dependent upon the standardised concentration of the stock solution and the volume that could accurately be dispensed. All inactivation studies were conducted in batch experiments at 25°C ± 1°C in sterile 1 ℓ glass sample bottles. Test water was placed in the sample bottle and the pH was adjusted to the required value using a concentrated phosphate buffer solution (yielding a final concentration of ca. 20 mM) and a digital pH meter (Metler-Toledo MP120). Once 25°C and the required pH was reached a sample was taken to establish the original faecal coliform count (N_o). The monochloramine was added to the test water from the pre-prepared stock solution to obtain the relevant residual concentration. After addition of the monochloramine the pH of the solution was measured to ensure that the test was done at the correct pH. While continuously stirring the solution, 5 mℓ samples were removed at pre-selected contact times (between 2 and 40 min depending on the inactivation rate) and combined with 5 mℓ of a sterilised thiosulfate solution of sufficient strength to neutralise the monochloramine residual as reported by Ward et al. (1984). After dilution the surviving faecal coliform bacteria were counted taking into account the dilution of the neutralising thiosulphate solution.

Inactivation in continuous-flow systems

To extend the batch inactivation studies to continuous-flow systems, two bench-scale chlorine contact tanks (CCT) were constructed from Plexiglas. The first CCT consists of eight identical CSTRs in series and the second CCT was a narrow channel with a small initial mixing chamber. Figures 1 and 2 show schematic diagrams of each CCT. These two CCT configurations were chosen to correlate mixing data (from tracer studies) and observed bacterial inactivation with inactivation predicted from the batch inactivation studies. Inactivation studies were conducted in each CCT by feeding test water and monochloramine solution at a constant rate and allowing the system to reach steady state by passing three reactor volumes of feed through the reactor. After steady state was reached in Reactor 1, bacterial samples were taken of the feed water as well as in each of the eight cells. In Reactor 2 samples of the feed and the reactor effluent were taken and analysed for faecal coliform numbers. The operating conditions and results of this experiment are shown in Table 3.

Enumeration of bacteria

The test organism used was the faecal coliform group as specified by the South African Bureau of Standards. Enumeration of bacteria was conducted using the membrane filter technique; method 9222D (*Standard Methods*, 1989). Samples were diluted into decimal dilution series using sterilised water. Appropriate volumes of water were passed through sterile 0.45-µm pore-size cellulose nitrate filters (Whatman WCN type) and washed with sterilised wash water. The membranes were removed and placed on commercial m-FC agar media (Merck Biolab medium C29) for the enumeration of faecal coliforms. All colonies with a blue colour were counted after incubation at 44°C for 24 h and bacterial concentrations in the original samples were calculated.

Tracer studies

The mixing regime in each CCT was determined by conducting tracer studies with lithium as tracer. All tracer experiments were done as pulse inputs. The constant flow in each reactor was adjusted to reflect the flow rate used in the continuous flow inactivation studies. Samples were taken of the reactor effluent at constant time intervals of one minute and analysed with an atomic absorption spectrophotometer (Varian AA-1275, Air-Acetylene).

Data analysis

To find the most accurate model for batch inactivation kinetics, the data obtained from the batch inactivation studies were fitted to Eqs. (1), (3), (4) and (5). (Eq. (1) showed significant deviation from the observed data and no further attempt was made to use this equation). Equation (3) was linearised and fitted with Microsoft Excel 97 software (Microsoft Corporation, California, 1993) using linear regression. Equation (4) was fitted using a spreadsheet to obtain the

best fit value of *j* for a set of experiments conducted at a specific pH. This was done by evaluating the least sum of squares of deviation of the observed data to the predictions of Eq. (4). The least square best fit value of *K* was then recorded (Severin et al., 1984). Equation (5) was fitted with DataFit software (Oakdale Engineering, USA) using non-linear regression analysis and the best fit values of *k*, *m* and *n* were recorded for each of the experiments. The accuracy of each model was then evaluated by comparing the correlation coefficients (R^2) calculated for each model.

The following method was used to predict the survival ratios of bacteria in the effluent streams of the CCTs:

- The series-event model for a number of CSTRs in series (Eq. 6) was used (Severin et al., 1984).
- The value of K was graphically evaluated from Fig. 3 at the monochloramine concentration and pH at which the experiment was conducted.
- The best fit value of j = 2 was used as reported in Table 2.
- The N value for each reactor, as obtained from the tracer experiment, was used in Eq. (6).

Results and discussion

Batch inactivation studies

The fitted parameters and correlation coefficients (R^2) for each of the models evaluated are given in Table 2. Referring to Table 2, there are 5, 11 and 8 sets of data that can be fitted to Eqs. (3), (4) and (5) respectively with a correlation coefficient greater than 0.95. Equation (4) was not only found to be the model that best represented the experimental data, but also gave values for the apparent kinetic constant, K, that increased with an increase in monochloramine concentration and increased with decreasing pH as would be expected (see comparison with study by Ward et al. (1984)). The values of the kinetic reaction coefficients of the other two equations show a more random variation making it difficult to use them to predict disinfection efficiency. The relationship between K (Eq. (6)) and monochloramine concentration is shown in Fig. 3.

The relationship between monochloramine concentration and the time required to effect a 99% reduction in faecal coliform numbers (t99) at three different pH values is shown in Fig. 4. The graph was generated using Eq. (3) to determine the t99 values. The data are presented in this way (i.e. using Eq. (3) instead of (4)) so as to compare the data obtained in this study to results obtained by other workers who presented their data in this way. A study by Ward et al. (1984) who used monochloramine, *E. coli* and chlorine demand-free solutions is shown on the same graph (Fig. 4) for comparison. The disinfection efficiency measured in this study compares relatively well to that measured by Ward under demand-free conditions. This indicates that the disinfectant capability of monochloramine is not significantly influenced by chlorine demand-causing materials as is the case with free chlorine. The disinfection efficiency measured in this study was less sensitive to pH than that measured by Ward (1984).

Tracer studies

The tracer response curves for each of the two CCTs are shown in Figs. 5 and 6 respectively along with the theoretical curve for the corresponding number of theoretical CSTRs (N) obtained by analysis with the tanks-in-series-model.

The results show that the mixing regime in Reactor 1 corresponds to that of 11 CSTRs in series (N = 11), while the mixing regime in Reactor 2 approaches plugflow conditions (N = 59).

Figure 1
CSTRs in series (Reactor 1)

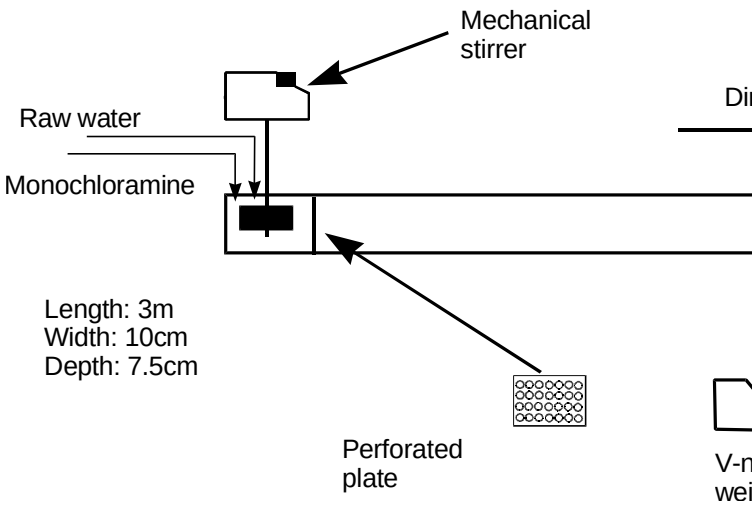

Figure 2
Channel (Reactor 2)

TABLE 2
COMPARISON OF THE CORRELATION OF DIFFERENT KINETIC MODELS FOR BATCH INACTIVATION STUDIES

Exp. No.	$[NH_2Cl]$ mg/ℓ	Equation (3)			Equation (4)			Equation (5)			
		k'	m	R^2	j	K	R^2	k	m	n	R^2
1	1.4	0.281	0.928	0.981	2	0.305	0.963	0.036	1.859	0.139	0.972
2	2.4	0.361	0.715	0.845	2	0.883	0.932	0.055	2.613	0.584	0.973
3	3.4	2.188	0.455	0.874	2	1.186	0.999	ND	ND	ND	ND
4	4.4	0.158	2.405	0.898	2	2.180	1.000	ND	ND	ND	ND
5	1.0	0.062	1.303	0.907	2	0.238	0.989	0.000	5.199	0.698	0.995
6	1.7	0.029	1.774	0.884	2	0.417	0.986	0.002	5.183	1.317	0.980
7	2.4	0.462	0.943	0.890	2	1.180	0.998	0.179	1.108	0.113	0.993
8	3.3	0.547	1.230	0.928	2	1.337	0.999	0.218	1.793	0.593	0.905
9	4.6	1.714	0.678	0.994	2	0.318	0.943	0.038	1.628	0.055	1.000
10	1.2	0.065	1.282	0.961	2	0.562	0.973	0.129	1.450	0.144	0.996
11	2.5	0.081	1.475	0.950	2	1.137	1.000	0.119	2.412	0.601	0.947
12	3.8	0.782	0.798	0.965	2	2.14	1.000	0.412	1.117	0.220	0.974
13	4.7	6.383	0.744	0.746	2	0.952	0.982	ND	ND	ND	ND

ND = Could not be fitted to model due to insufficient number of data points on inactivation curve.

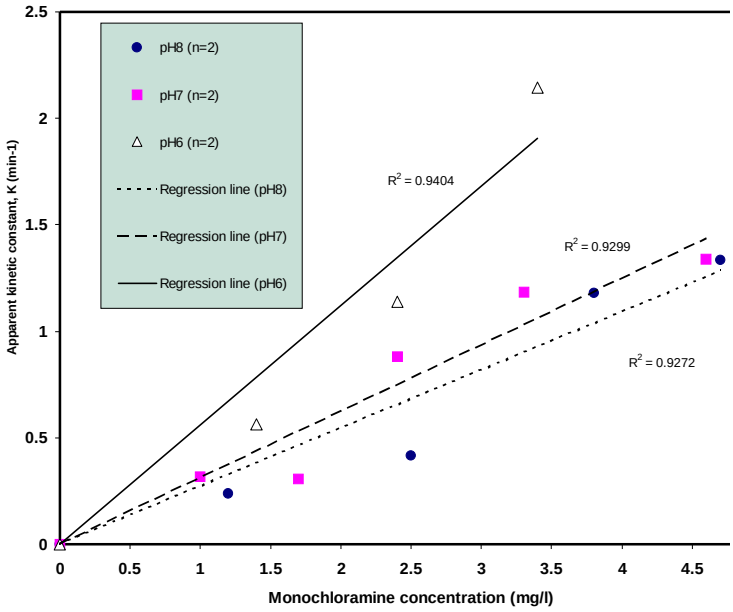

Figure 3
The relationship between the apparent kinetic constant (K) and monochloramine concentration as measured at different pH values in batch experiments

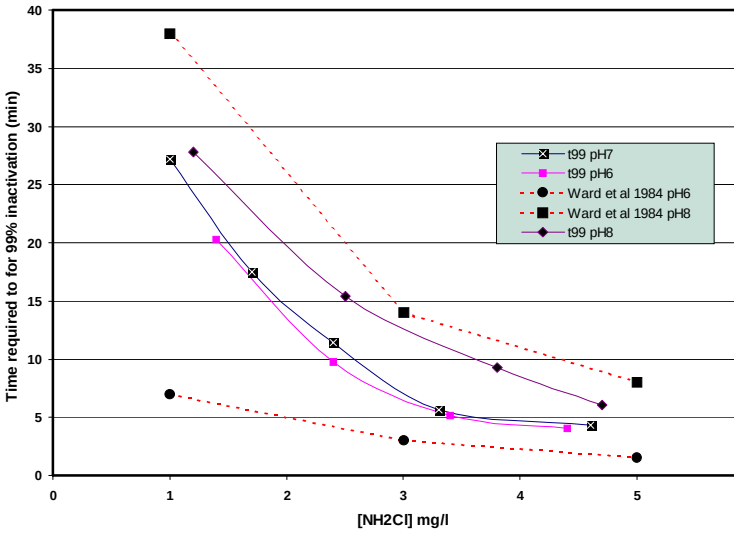

Figure 4
A comparison between the disinfection efficiency obtained in this study and that measured by Ward et al. (1984) at different pH values and monochloramine concentrations

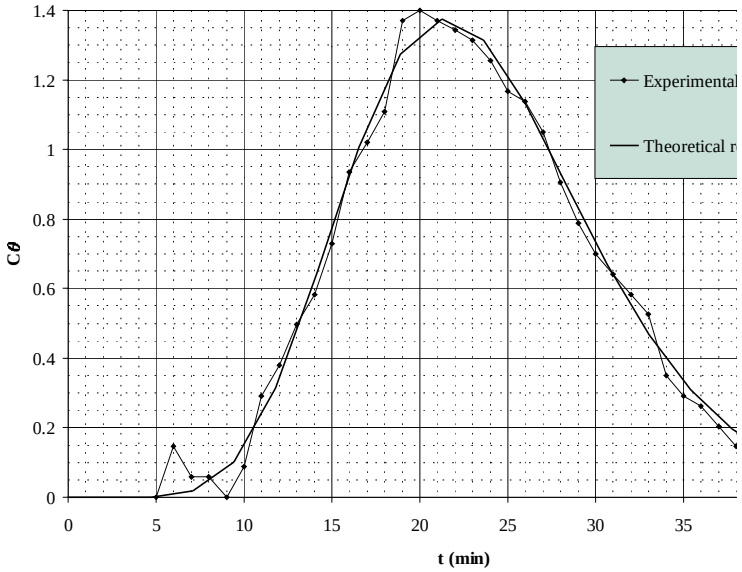

Figure 5
Experimental and theoretical tracer response curves for Reactor 1

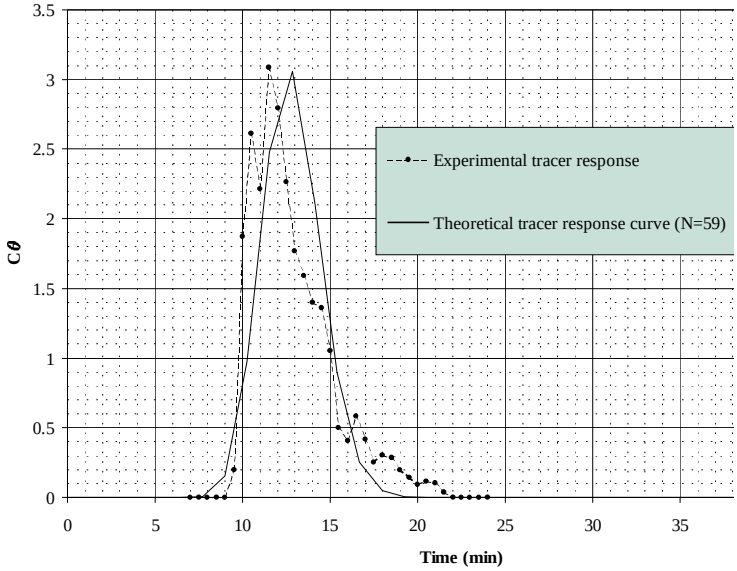

Figure 6
Theoretical and experimental tracer response curves for Reactor 2

Inactivation in continuous flow systems

The inactivation of faecal coliforms as measured in the continuous flow CCTs are summarised in Table 3 along with the predicted survival ratios as calculated by means of Eq. (6). Survival ratios for Reactor 1 were predicted (Eq. 6) for each cell in the reactor. (The tracer study showed that the reactor was equivalent to 11 theoretical CSTRs. It was therefore assumed that each of the 8 physical cells was equivalent to 11/8 theoretical CSTRs).

Equation 6 was also used to predict survival ratios for reactor 2 (N = 59). As shown in Table 3 the predicted and observed ratios corresponded well for this reactor too. When the predicted survival ratios are compared to the measured ratios, a good correlation ($R^2 = 0.94$) is observed as shown in Fig. 7.

TABLE 3
COMPARISON BETWEEN OBSERVED AND PREDICTED INACTIVATION IN THE CONTINUOUS FLOW SYSTEMS

Reactor 1	**pH = 7.39; [NH_2Cl] = 0.8 mg/ℓ; Temperature = 21°C**	
Sample	**Nt/No (observed)**	**Nt/No (predicted, N = 11)**
Cell1	0.557	1.271 (not applicable)
Cell2	0.391	0.495
Cell3	0.313	0.266
Cell4	0.174	0.148
Cell5	0.100	0.083
Cell6	0.072	0.047
Cell7	0.041	0.027
Cell8	0.016	0.015

Reactor 2				
Experiment	**pH**	**[NH_2Cl] mg/ℓ**	**Nt/No (observed)**	**Nt/No (predicted)**
Run 1	7.01	1.2	0.029	0.032
Run 2	7.00	2.1	0.006	0.002

Conclusions

- This study shows that the disinfectant capability of monochloramine is not significantly affected by chlorine demand-causing materials as is the case with free chlorine.

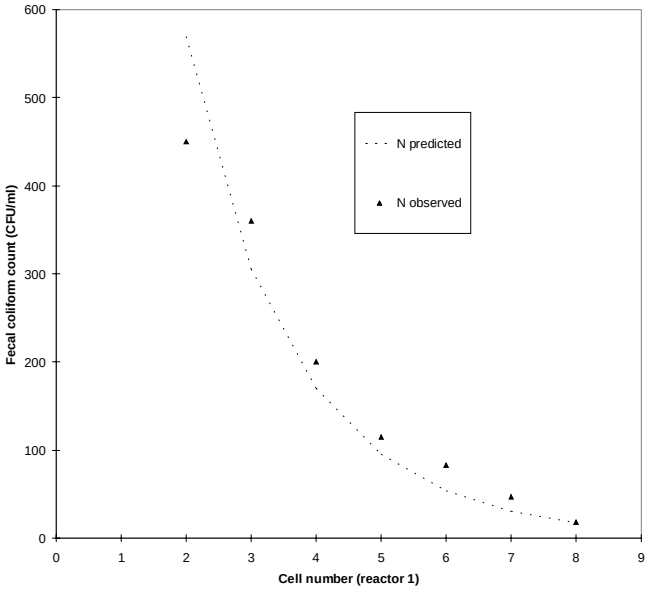

Figure 7
Evaluation of the predictive capability of Eq. (6)

- The effect of pH on the disinfectant capability of monochloramine as measured in this study was not as significant as measured by Ward et al. (1984).
- Of the three models evaluated for accuracy in the batch inactivation experiments, the series-event kinetic model (Eq. (6)) gave the best fit to the measured data.
- The fitted parameter of the series-event model, K, displayed a more consistent variation with monochloramine and pH concentration while the reaction coefficients of the other models vary in a more random fashion. This makes the series-event model the most suitable inactivation model for the water tested.
- The series-event model combined with the tanks-in-series model gives accurate predictions of the survival ratios measured in the continuous-flow systems.
- The series-event model in combination with a tracer study provides an accurate method to predict the performance of a continuous-flow CCT from batch inactivation studies using monochloramine as disinfectant.
- This study shows that the behaviour of a continuous-flow CCT can be accurately predicted from batch experiments conducted in the laboratory. This provides a method that employs data from simple batch experiments conducted in the laboratory for the design of continuous-flow monochloramine disinfection systems.

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Appendix: Design example

The following example is included to show how the method discussed above can be applied to a situation where a chloramination system is to be retrofitted to an existing CCT. The following data are available:

TABLE A1
AVAILABLE DATA

Parameter	Units	Value
Volume of CCT (V)	m^3	450
Flow rate (F)	m^3/min	30
Theoretical hydraulic retention time (T)	min	15
Design pH	pH	7.0
Desired effluent faecal coliform count	CFU/100 mℓ	<1
Initial faecal coliform count	CFU/100 mℓ	100 000

The objective is to determine the monochloramine concentration required to obtained a desired inactivation of faecal coliform bacteria.

Step 1

Conduct a tracer study on the CCTs and analyse the data with the tanks-in-series model. The following table contains typical data obtained from a tracer experiment where 400 g of lithium was injected as a pulse input into the CCT described in Table A1:

TABLE A2
DATA OBTAINED FROM TRACER STUDY

Time (min)	Lithium concentration (mg/ℓ)	θ	Cθ	Recovery of lithium (g)
1	0.03	0.07	0.03	0.80
2	0.02	0.13	0.03	0.69
3	0.04	0.20	0.04	1.07
4	0.03	0.27	0.03	0.91
5	0.04	0.33	0.04	1.07
6	0.04	0.40	0.05	1.25
7	0.14	0.47	0.15	4.11
8	0.36	0.53	0.40	10.75
9	0.50	0.60	0.56	14.88
10	0.77	0.67	0.87	23.10
11	0.95	0.73	1.06	28.37
12	1.16	0.80	1.30	34.65
13	1.23	0.87	1.39	36.96
14	1.25	0.93	1.41	37.60
15	1.26	1.00	1.43	37.76
16	1.08	1.07	1.21	32.27
17	0.93	1.13	1.05	28.03
18	0.79	1.20	0.89	23.79
19	0.69	1.27	0.78	20.69
20	0.50	1.33	0.56	14.93
21	0.38	1.40	0.43	11.33
22	0.33	1.47	0.37	9.84
23	0.20	1.53	0.23	6.05
24	0.17	1.60	0.19	5.15
25	0.10	1.67	0.11	2.85
26	0.08	1.76	0.09	2.34
27	0.05	1.80	0.06	1.59
28	0.05	1.87	0.06	1.60
			Total mass	**394.4**

To obtain the tracer response curve, Cθ is plotted vs. θ. Where Cθ and θ are normalised concentration and time values respectively. These values are calculated as follows:

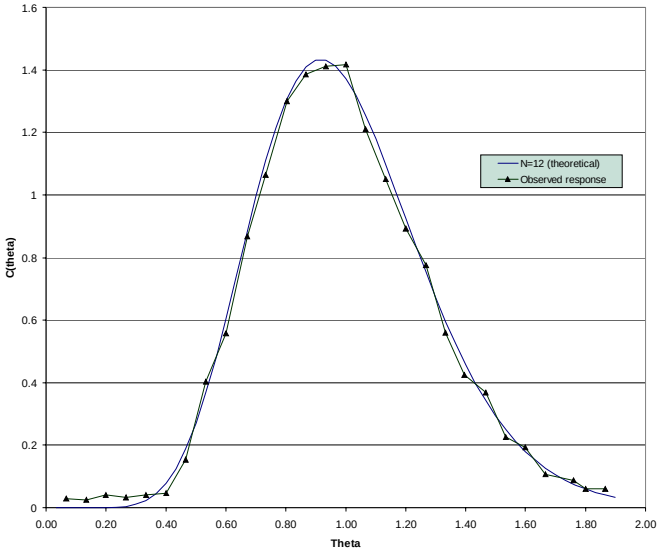
$$C\theta = \frac{\text{Concentration (C)}}{\text{Dose concentration } (C_o)}$$

and

$$\text{Dose concentration } (C_o) = \frac{\text{Mass of tracer injected}}{\text{Reactor volume (V)}}$$

$$\theta = \frac{\text{Time (t)}}{\text{Theoretical hydraulic retention time (T)}}$$

The tracer response data are represented on the curve below:



The recovery for each time interval is calculated as the product of the measured tracer concentration in the interval, the time elapsed in the interval and the flow. (Mass = C x Δt x F). The total recovery is then determined by obtaining the sum of recoveries over all the time intervals:

$$\text{Tracer recovered} = \frac{\text{Sum of recoveries}}{\text{Mass of tracer injected}}$$

$$= \frac{394.4\text{g}}{400\text{g}} = 98.6\%$$

To obtain the number of theoretical CSTRs equivalent to the CCT, the maximum value of Cθ, ($C\theta_{max}$), is used together with the following equation and solving for N:

$$C_{\theta_{max}} = \frac{N(N-1)^{N-1}}{(N-1)!} e^{-(N-1)}$$

From Table A2, $C\theta_{max}$ is equal to 1.43 which corresponds to N = 12.

Step 2

Determine the required survival ratio (N_e/N_i):

$$\frac{N_e}{N_i} = \frac{\text{Count required in effluent}}{\text{Initial count}} = \frac{1}{100\,000} = \frac{N_t}{N_0}$$

Step 3

Use Eq. (A-1) to determine the apparent kinetic constant, K, required to obtain the desired inactivation (survival ratio):

$$\frac{N_t}{N_o} = \left(\frac{1}{1+K\tau'}\right)^N \cdot \sum_{i=0}^{j-1} \left[\frac{i+N-1}{N-1}\right]\left(\frac{K\tau'}{1+K\tau'}\right)^i \qquad \text{(B-1)}$$

Use the best fit value of j = 2 as obtained in the experimental work above (this may vary from one effluent to another). The value of τ' is obtained by dividing the theoretical retention time of the CCT by the N value obtained in **Step 1** (N = 12). Thus τ' = 1.25 min.

Substitute the values of τ' (1.25 min), N (12) and the survival ratio, N_t/N_o (0.0001), and calculate the corresponding value of K. The K value obtained in this way is 1.34 min^{-1}.

Step 4

Use the K value obtained in Step 3 (1.34 min^{-1}) and evaluate the monochloramine concentration required at the relevant pH (pH 7) from Fig. 3. At this K value and pH, a monochloramine concentration of 4.2 mg/ℓ is required to effect the desired inactivation of faecal coliforms.