Effect of flow velocity on chlorine decay in water distribution network: a pilot loop study

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Experiments were run in the pipe loop setup to estimate bulk and wall chlorine decay rates under varying flow and chlorine levels for groundwater. A recirculating loop of 50 mm inner diameter polyvinyl chloride pipe and a variable flow pump with feed and recirculation tank were used to design a pipe loop. Sodium hypochlorite was introduced as free chlorine into the test water. The study came up with three important findings: (a) bulk chlorine decay rate in test water decreased with increase in chlorine levels, which is attributed to the type and level of organic matter present in test water. (b) Chlorine decay rate in pilot loop setup increased with increase in flow velocity. The result showed that under turbulent conditions, in addition to chlorine, mass flux transfer from bulk to wall and biofilm removal from pipe surface contributed to chlorine decay. We also noted that with increase in flow velocity the contribution of bulk reaction to total chlorine decay in pipe loop decreased. (c) ANOVA test on experimental dataset showed that as compared to initial chlorine levels, flow velocity has statistically significant effect on chlorine dissipation in a pipe loop. We also found that after turbulent flow is achieved, the effect of flow velocity on the wall decay is negligible.

Keywords: Chlorine decay, pipe loop setup, Reynolds number, water distribution systems.

MAINTAINING 0.2 mg/l of residual chlorine in a distribution system is one of the several challenges faced by public health utilities in the developing world. Most cities in India have intermittent water supply systems where water is supplied to consumers only for few hours per day for two to three days in a week[1]. The raw water is either sourced from a nearby river or from the local aquifer. In both the cases, it is important to estimate the levels of chlorine dosage in the overhead tank so that a minimum of 0.2 mg/l of chlorine is retained till the water reaches the end consumer.

There are several factors that lead to the decay of chlorine in water distribution network. Field and laboratory studies have shown that the chlorine decay in distribution system depends on the pipe material, water quality and temperature. Chlorine dissipates as it reacts with organic matter present in the water and the organic matter attached to the pipe surface (also called as biofilm). Past studies have reported an increase in the rate of biofilm growth when water distribution network is subjected to flow/non-flow conditions[2,3]. Few studies have also suggested that the biofilm in addition to consuming residual chlorine in water also shields harmful bacteria from chlorine oxidation[4,5].

Chlorine decay in distribution network depends on the reaction that occurs both within the bulk water and biofilm attached to the pipe[6]. Chlorine bulk decay rate depends on the initial chlorine (IC) levels, whereas chlorine-wall decay rate depends on the biofilm thickness, pipe age and pipe material[7]. The overall chlorine dissipation within the distribution network is represented mathematically by eq. (1). The overall decay rate constant is equal to the sum of bulk and wall decay rate.

$$\frac{dC}{dt} = -K_{total}C = -(K_{bulk} + K_{wall})C, \quad (1)$$

where K_{total} is the overall chlorine decay constant in the pipe (1/day), K_{bulk} the chlorine decay constant in bulk water (1/day) and K_{wall} is the wall reaction constant (1/day).

Various studies reported that the wall reaction rate (K_{wall}) depends on the flow velocity, wall rate constant and surface–volume geometry of pipe (pipe diameter)[6,7]. Therefore, overall wall decay constant could be expressed as follows

$$K_{wall} = \frac{4(k_f * k_w)}{D(k_f + k_w)}, \quad (2)$$

where D is the pipe diameter (m), k_w the wall constant (m/day) and k_f is the mass transfer rate constant (m/day).

The mass transfer constant k_f is related to the Sherwood number (S_h), which depends on Reynolds number (R_e). k_w is an intrinsic property of pipe material, hence is a constant[7].

The mass flux constant (k_f) depends on the flow velocity and pipe diameter and is expressed as

$$k_f = S_h \text{ (diffusivity/diameter)}. \quad (3)$$

Diffusivity of chlorine = 1.44×10^{-5} cm^2 s^{-1}.

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The Sherwood number (S_h) depends on the Reynolds number, therefore at

Re < 1: $S_h = 2.0$,

Re > 2000: $S_h = 0.0149 R_e^{0.88} S_c^{0.33}$.

The Schmidt number (S_c) is equal to the kinematic viscosity of water divided by the diffusivity of chlorine.

Chlorine decay models are used to estimate bulk and wall decay rate constant (under varying conditions). These models, after validations are used for estimation and prediction of chlorine within the water distribution network.

Many cities in developing countries are water scarce and half of the total water supplied is pumped from the aquifers[8]. The aquifer water is considered 'safe' and, therefore a minimal amount of chlorine is added to reduce the health impact. In earlier studies, chlorine decay models have been extensively developed and used to estimate chlorine decay rate for surface water without paying much attention to groundwater[9,10]. Therefore it is very important to understand chlorine decay in groundwater as it possesses different water quality characteristics (organic and inorganic material) as compared to the surface water. Through this study, we intend to (a) estimate chlorine decay rates (both bulk reaction and wall reaction) in groundwater distribution systems; (b) understand the effect of flow velocity and IC levels on chlorine decay and (c) understand the contribution of biofilm release on wall reaction rate.

Methodology

To conduct the planned set of experiments, water was collected from a borewell located in the northern part of Bengaluru city. The water depth in the designated borewell was between 600 and 700 feet. As the test water was obtained from a deep aquifer, we assumed that water quality characteristics of test water (groundwater) remained constant over a period of time. As bulk chlorine reaction in water is not affected by pipe material; therefore, we employ bench-scale experiments to study bulk decay. The total chlorine decay was estimated by running chlorine decay tests in pilot loop setup at Water and Soil Laboratory at ATREE. The incubation temperature for bench-scale test was set equal to the ambient water temperature in the pilot loop. We estimated the contribution of wall reaction to total chlorine dissipation in pipe loop as the difference between the total chlorine and bulk chlorine reaction rates. We used statistical analysis (ANOVA) to compare the effect of individual factor (IC levels or flow velocity) as well as combination of factors (IC levels and flow velocity) on chlorine reaction rate in pipe loop.

Temperature correction

As ambient temperature varied with season, the experimental runs for bulk and pipe loop were carried out at different temperatures. To compare decay test results, we used van't Hoff–Arrhenius approach (eq. (3)) to estimate bulk and total decay constants at 20°C (ref. 7). For this, we first estimated conversion factor (θ) by conducting bench-scale chlorine decay test at 20°C and 30°C at IC level of 6 mg/l. Chlorine in the test water was measured every 4 h for 4 days.

$$k_{b_2} = k_{b_1} \theta^{(T_2 - T_1)}, \tag{4}$$

where k_{b_2} and k_{b_1} are chlorine decay constants at temperature T_2 (30°C) and T_1 (20°C).

Bench-scale test

Simultaneously, we carried out bench-scale tests on feed water to estimate the contribution of bulk decay rate to overall chlorine decay in the pipe loop. The bulk decay tests were done for IC levels of 3 and 6 mg/l. Each experiment was carried out for 12 h. Higher IC levels in the feed tank ensured that measurable levels of free chlorine were present even after 12 h. Amber glass bottles were filled with the feed water and kept at a constant temperature in the incubator. The incubator temperature was set at the same temperature as in the pilot loop. Hourly samples were drawn from the bottles and free chlorine levels were measured for 12 h. Free chlorine in the test water was measured using HACH calorimeter. Free chlorine measurement range of instrument varied from 0.1 to 5.0 mg/l; therefore, water samples levels greater than 5 mg/l were diluted for measurement of free chlorine.

Temperature, pH, alkalinity and hardness level of the test water being fed to the pipe were also measured. The bench-scale tests were run parallel to the pilot loop tests. Table 1 presents the water quality parameters of test water.

Pipe loop setup

We fabricated pipe loop to simulate flow velocity at different chlorine levels in test water. Figure 1 presents the

Table 1. Characteristics of groundwater quality

Parameter	Average level (n = 3)
pH	6.75
Conductivity	1150 µS/cm
Nitrates	177 mg/l
Hardness	352 mg/l
Alkalinity	165 mg/l

line diagram and photograph of the pipe loop built at the Water and Soil Lab at ATREE. The length of the pipe loop is 12.5 m. It is made up of polyvinyl chloride (PVC) pipe with 52 mm internal diameter. There are two tanks, viz. the feed tank and the recirculation tank in the pipe loop. A feed tank (150 litres capacity) is mounted 2 m above the pipe loop to feed test water to pipe loop by gravity. It holds the feed water for 2 h and allows uniform mixing of chlorine in the feed water. Recirculation tank is used to hold feed water for recirculation. Variable flow pump is introduced to simulate laminar, transition and turbulent flow in the pipe. Flow meter mounted on the pipe loop records the flow in litres per minute (lpm). The heat exchanger is installed in the pipe loop along with the temperature sensors to maintain constant feed water temperature during the experimental run. When kinetic experiments are not being run, the pipe loop is kept under maintenance mode by introducing test water to it at 0.08 lpm through the recirculation tank. This results in 15 h retention time of water in the pipe loop.

Experimental run

For each experiment, we added sodium hypochlorite solution into test water in feed tank and mixed it thoroughly to achieve IC levels of 3 and 6 mg/l. The chlorinated water was held for 2 h before it was introduced into the pipe loop. The pipe loop was flushed twice before being filled with feed water so as to ensure removal of old water from the system. The pipe loop was filled with the feed water (150 litres) and was circulated in the pipe loop. The variable flow pump frequency was set at the desired levels and flow in the pipe was recorded accordingly. The time taken by the feed water to complete one pass in the pipe loop depends upon the flow velocity. Table 2 presents the flow velocity and distance covered by test water for each experimental setup. Hourly samples were collected from the sample port in the pipe loop for free chlorine measurement. The duration of the experimental run was 12 h. For better repeatability of chlorine decay test in the loop, one-week maintenance run between two experiments was kept[6]. This condition allowed the biofilm to grow and ensured similar initial condition for all the experimental runs.

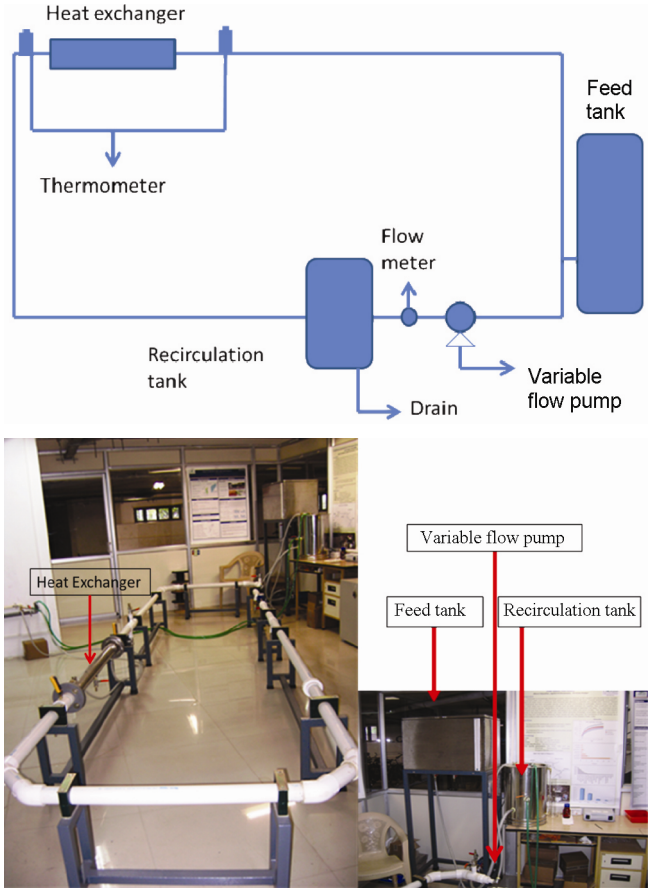

Figure 1. Line diagram and photograph of pipe loop setup.

Estimation of kinetic parameters

Assuming chlorine decay in the pipe loop follow first order decay equation (eq. (1)), K_{bulk}, K_{total} were estimated for time series data of chlorine decay in pipe loop and bench-scale test for each experiment. The overall decay constant was estimated using least square regression by setting intercept to 0 of the quantity $\log(C_t/C_0)$ against time, where C_t is the concentration at time t and C_0 is the initial concentration at time t equals to 0. The bulk decay constant was also computed in a similar way except that the chlorine concentrations were measured in the bulk test water. The wall reaction constant was estimated as a difference between overall decay constant and the bulk decay constant.

Results

Temperature effect

To assess the effect of flow velocity and IC levels on chlorine decay, we wanted to compare bulk and chlorine decay rates for experimental runs. As experimental runs, we carried out at ambient temperature for comparison, we corrected decay rate constants using eq. (3). We estimated correction factor (θ) by conducting chlorine decay bench-scale test at two different temperatures at constant IC level. Figure 2 presents a fraction of chlorine remaining in test water at 20°C and 30°C at IC levels of 6 mg/l. Table 3 presents the bulk decay constants and estimated correction factor (θ) value.

Bulk chlorine decay

Using the correction factor, we estimated the bulk decay rate constants at IC level 3 and 6 mg/l at 20°C. Figure 3

Table 2. Experimental runs in the pipe loop setup

Flow (m^3/day)	Velocity (m/s)	Reynolds number	Distance (km)	IC levels (mg/l)	Number of runs (n)
6	0.03	1949	1.5	3, 6	1, 1
8	0.05	2795	2.1	3, 6	2, 2
12	0.07	4003	3	3, 6	2, 2
20	0.12	6733	5	3, 6	2, 2

Table 3. Correction factor (θ)

	(1/day)		
Type of water	20°C	30°C	θ
Groundwater (K_{bulk})	0.0192	0.024	1.02

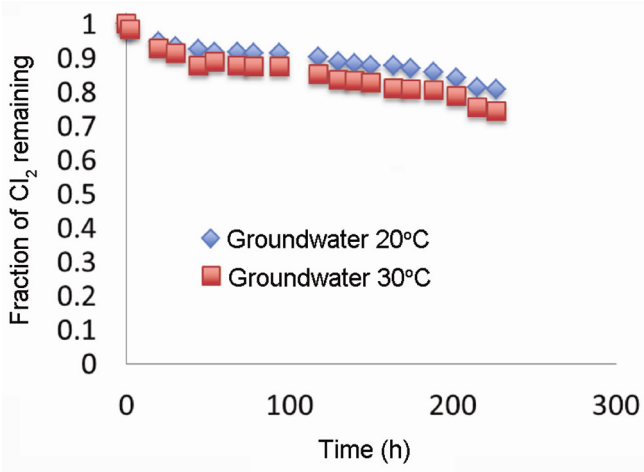

Figure 2. Effect of temperature on bulk chlorine decay in groundwater.

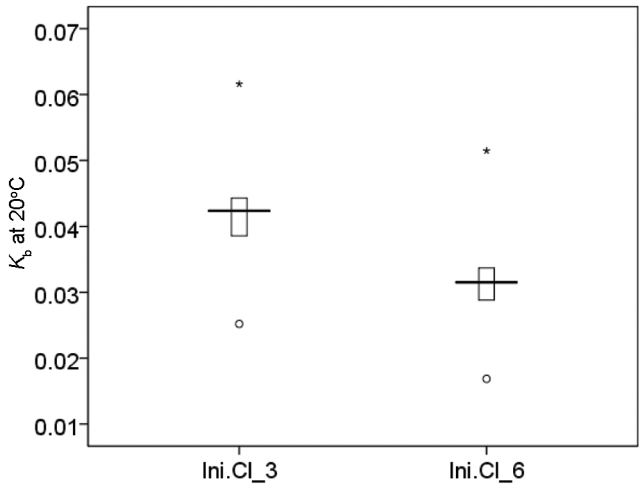

Figure 3. Effect of initial chlorine levels (3 and 6 mg/l) on bulk decay constant (K_{bulk}).

presents the average bulk decay rate constant observed at 3 and 6 mg/l. The average bulk decay constant observed at IC of 3 mg/l was twice as that for IC level of 6 mg/l. This indicated that chlorine dissipated much faster when IC level in piped water is low which could be attributed to the percentage of fast and slow reacting organic matter present in water. Our findings were in line with other studies which suggested that chlorine decay in bulk water does not follow simple first order decay models; therefore, bulk chlorine decay should be modelled taking into consideration the fast and slow reactant organic matter[11].

Wall reaction rate

Modelling and prediction of chlorine levels within the distribution system requires a thorough knowledge of factors/processes responsible for chlorine decay. We investigated the role of IC and flow velocity of chlorine decay within the pipe loop. The tests were carried out at two IC levels, i.e. at 3 and 6 mg/l and at different flow velocities (Table 2). The flow velocity in the pipe loop varied from 0.02 m/s (laminar flow) to 0.12 m/s (turbulent flow).

Figure 4 presents the fraction of chlorine remaining in the pipe loop at IC levels of 3 and 6 mg/l at different flow velocities. The data showed that the fraction of chlorine remaining in test water decreased with increase in flow velocity. The literature suggests that at higher flow velocity, chlorine mass flux transfer from bulk to the wall increases which in turn increases the rate of chlorine decay[6]. We also observed a decrease in chlorine reaction rate with increase in chlorine levels suggesting that the fast and slow reacting organic matter effects chlorine decay in pipe loop[7]. Table 4 presents the estimated total, wall and bulk decay constants at 20°C.

To assess the effect of flow velocity on chlorine wall decay rate, we estimated the wall constant (k_w) and mass transfer constant (k_f) using eqs (2) and (3) respectively (Table 5).

Our results showed that k_w is affected both by chlorine levels and flow velocity. When flow changed from laminar (R_e – 1950) to turbulent (R_e – 6730), wall constant increased by 60% (3 mg/l) and 66% (6 mg/l). These results are in contrast with the results reported by other studies which suggested for PVC pipes k_w remains a constant value[6,7]. We hypothesized that increase in k_w observed at

Table 4. Total, bulk and wall decay constant for variable flow and IC levels

	3 mg/l, R_e				6 mg/l, R_e			
Decay constants at 20°C	1950 (n = 1)	2780 (n = 2)	4000 (n = 2)	6730 (n = 2)	1950 (n = 1)	2780 (n = 2)	4000 (n = 2)	6730 (n = 2)
K_{total} (1/day)	0.33	0.23	0.23	0.30	0.24	0.18	0.33	0.33
K_{bulk} (1/day)	0.22	0.04	0.04	0.04	0.14	0.03	0.05	0.03
K_{wall} (1/day)	0.11	0.19	0.19	0.26	0.10	0.15	0.28	0.30

Table 5. Chlorine mass transfer flux constant and PVC wall constant for various simulations

Flow (m^3/day)	Velocity (m/s)	R_e	S_c	Diffusivity of chlorine (m^2/s)	S_h	Diameter (m)	k_f (m/day)	k_w (m/day)	
								3 mg/l	6 mg/l
20	0.12	6733	694	1.44E-09	302	0.052	0.72	0.0036	0.0042
12	0.07	4003	694	1.44E-09	191	0.052	0.46	0.0027	0.0039
8	0.05	2795	694	1.44E-09	139	0.052	0.33	0.0027	0.0021
6	0.03	1949	694	1.44E-09	31	0.052	0.08	0.0015	0.0014

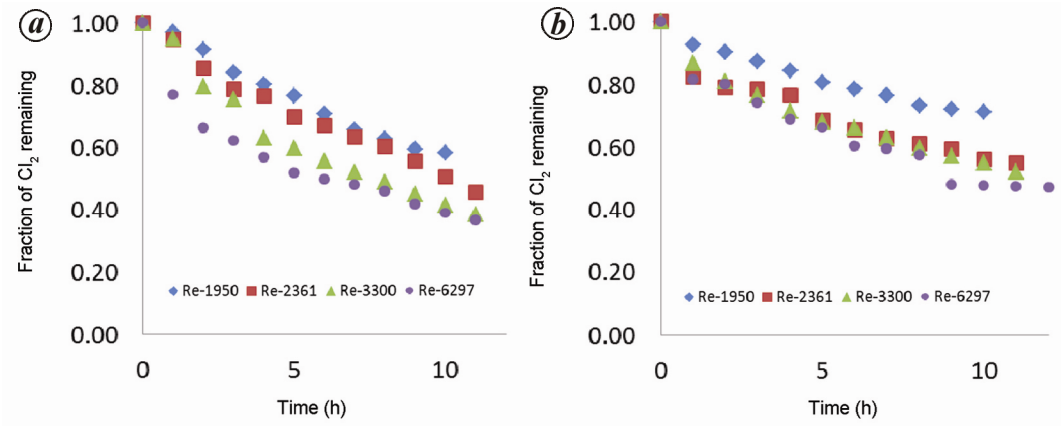

Figure 4. Fraction of free chlorine remaining in pipe loop at IC levels (***a***) 3 and (***b***) 6 mg/l.

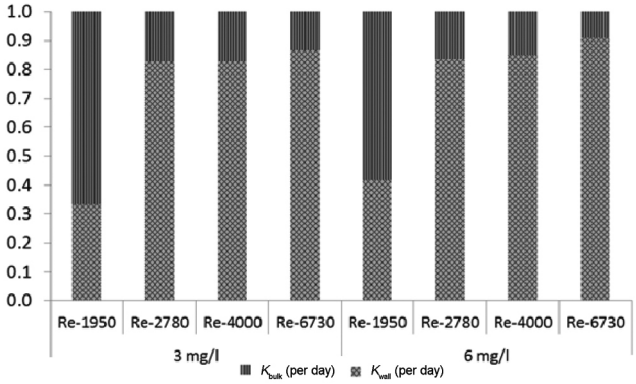

Figure 5. Relative contribution of bulk and wall reactions to total chlorine decay in pipe loop.

higher velocity could be attributed to organic matter release from pipe wall which accelerated the rate of chlorine consumption. This hypothesis is supported by other studies that reported higher cell counts in the biofilm formed on PVC as compared to copper or polyethylene pipe surfaces[12–14]. Another study reported that the organic matter released is directly proportional to the shear stress exerted on the walls as water flows in the pipe which become constant after attaining a certain velocity[15]. Few other studies reported that rapid changes in water flow cause release and re-suspension of biofilms in distribution network which impart turbidity to piped water[16].

Our results supported the findings which suggest that modelling of chlorine decay in water distribution network should also include the re-suspension/detachment term[17]. This is especially important in the context of intermittent water supply systems where water pipes are prone to higher biofilm growth rates due to frequent flow/non-flow conditions[3].

Figure 5 presents the relative contribution of bulk and wall reaction to total chlorine decay in pipe loop. The data revealed that during low flow conditions (laminar flow), bulk reaction contributed to 70% of the total chlorine decay in the pipe loop and as the flow shifted from

laminar to turbulent, wall reaction dominated the chlorine decay in the pipe loop. For $Re > 2000$ contribution of wall reaction to total chlorine decay was greater than 80%.

An analysis of variance was applied to the results shown in Table 4 to observe if the IC level or the flow velocity or both the factors have any statistically significant effect on the wall reaction rate. The results showed that flow velocity has a significant impact on the wall reaction rate as compared to IC levels and both factors together did not have a significant impact on the wall reaction rate.

Conclusion

In this study, we assessed the effect of flow velocity and IC levels on wall and bulk decay constant for groundwater using the pilot loop setup. We also estimated the contribution of bulk and the wall reactions rate to total chlorine decay in PVC pipes. The study concluded as follows.

1. Bulk decay rate constant decreased with the increase in IC levels. Average bulk decay constant at IC level of 3 and 6 mg/l were 0.045 and 0.030 per day respectively. This suggests that chlorine decay in bulk water cannot be explained by simple first order equation. In addition to IC levels, nature and level of organic matter present in feed water also affects chlorine reaction in bulk water.

2. Contribution of bulk reaction rate to total chlorine decay decreased with increase in flow velocity. As flow changed from laminar to turbulent, the contribution of bulk reaction to total chlorine decay reduced from 70% to less than 20%.

3. Irrespective of the IC levels, the relative contribution of biofilm to chlorine decay increased with increase in flow velocity which could be attributed to the release of biofilm from the pipe wall.

4. ANOVA results indicated that flow velocity had a significant impact on the wall reaction rate as compared to IC levels. The results also indicate that after turbulent flow velocity is attained, the impact of flow velocity on wall decay becomes insignificant. The tests also suggest that both factors together did not have any significant impact on the wall reaction rate.

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