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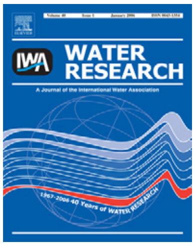

Chlorine decay in drinking-water transmission and distribution systems: Pipe service age effect

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ABSTRACT

Water quality can deteriorate in the transmission and distribution system beyond the treatment plant. Minimizing the potential for biological regrowth can be attained by chlorinating the finished water. While flowing through pipes, the chlorine concentration decreases for different reasons. Reaction with the pipe material itself and the reaction with both the biofilm and tubercles formed on the pipe wall are known as pipe wall demand, which may vary with pipe parameters. The aim of this paper was to assess the impact of the service age of pipes on the effective chlorine wall decay constant. Three hundred and two pipe sections of different sizes and eight different pipe materials were collected and tested for their chlorine first-order wall decay constants. The results showed that pipe service age was an important factor that must not be ignored in some pipes such as cast iron, steel, cement-lined ductile iron (CLDI), and cement-lined cast iron (CLCI) pipes especially when the bulk decay is not significant relative to the wall decay. For the range of the 55 years of pipe service age used in this study, effective wall decay constants ranged from a decrease by −92% to an increase by +431% from the corresponding values in the recently installed pipes. The effect of service age on the effective wall decay constants was most evident in cast iron pipes, whereas steel pipes were less affected. Effective chlorine wall decay for CLCI and CLDI pipes was less affected by service age as compared to steel and cast iron pipes. Chlorine wall decay constants for PVC, uPVC, and polyethylene pipes were affected negatively by pipe service age and such effect was relatively small.

1. Introduction

Disinfecting drinking water is considered important for the maintenance of water quality in transmission and distribution systems. Treated water is disinfected before it enters the transmission system (Clark and Coyle, 1990). Because bacterial contamination of water can be expected in the transmission and distribution system, a detectable disinfectant residual should remain in the water so that the potential for waterborne disease and biofilm growth will be minimized. Previously, the Water Research Centre (1976) had suggested some considerations for controlling bacterial numbers in treatment and distribution systems; these include system cleaning, limiting the retention time of the water in the network and the use of alternative disinfectants which may persist longer in the water.

Due to its low cost, stability, and effectiveness, chlorine is widely used for disinfecting water. Generally, a free chlorine residual in excess of 0.2 mg/l must be maintained in the distribution system, thus reducing the likelihood of further contamination. However, chlorine concentration decreases with time due to consumption. Clark et al. (1993) stated that the chlorine residual can virtually disappear at various times during the day. Maul et al. (1985a) concluded that the

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occurrences of the highest bacterial concentrations are attributed to lower levels of chlorine residuals and prolonged retention time of the water in the network. This temporal and spatial consumption of chlorine is caused by chemical reactions of the chlorine with water constituents and with both the biofilm and tubercles formed on the pipe wall, as well as reaction with the pipe wall material itself (Wable et al., 1991; Zhang et al., 1992; Kiéné et al., 1998). Deposits, corrosion by-products (Zhang et al., 1992; Kiéné et al., 1998; DiGiano and Zhang, 2005), microorganisms (Wable et al., 1991), organic impurities, ammonia compounds, and unremoved metallic compounds, such as iron (ferrous ions) and manganese, are among the constituents of water that react with chlorine and lead to its disappearance. Reaction with the pipe material itself and the reaction with both the biofilm and tubercles formed on the pipe wall are known as pipe wall demand. DiGiano and Zhang (2005) pointed out that reaction of chlorine on the scales coating the inner pipe surfaces is the main reason for the loss of such disinfectant within distribution networks. These reactions cause a decrease in the chlorine content in the water. Maul et al. (1985a) observed that there was a rapid decrease in both free and total chlorine residual in the water in the distribution system, as residence time increases while travelling from the treatment plant. Haas et al. (2002) observed that chlorine residuals loss averaged about 40% after 24 h of disinfecting of new pipes at high chlorine concentrations, such as during mains disinfection. The studies of Maul et al. (1985a, b) showed that free and total chlorine residuals decrease rapidly as distance from the treatment plant increases and free chlorine residuals disappear in the peripheral sections of the distribution system. Moreover, chlorine decay rates increase with an increase in water temperature. The results of the study on the Little Rock distribution system show that free chlorine residuals at 23 °C were less than the corresponding concentrations at 0–4 °C (Kirsch et al., 1994).

Chlorine consumption has been classified as occurring in two phases (Zhang et al., 1992; Kiéné et al., 1998). The first phase occurs during the first 1–2 or 4 h (Jadas-Hecart et al., 1992) and corresponds to reactions of the chlorine with easily oxidizable compounds. This is normally completed in the reservoir of the treatment plant. The second phase, or long-term chlorine consumption, is slower than the first phase and occurs in the distribution system. The second phase is normally described in terms of an apparent first-order equation (Wable et al, 1991; Biswas et al, 1993; Rossman et al., 1994; Kiéné et al., 1998) as follows:

$$\frac{dC}{dt} = -kC, \qquad (1)$$

where dC/dt is the of chlorine decay, mg/l per day, k, chlorine first-order kinetic constant or first-order decay coefficient, day^{-1}; C, chlorine concentration at time t, mg/l.

By integrating Eq. (1) and letting C equal C_0 when time t equals 0, the first-order kinetic equation used to describe chlorine loss is as follows:

$$C = C_0 e^{-kt} \quad \text{or} \quad \mathrm{Ln}\, C = \mathrm{Ln}\, C_0 - kt, \qquad (2)$$

where C_0, initial chlorine concentration, mg/l; t, time, days.

With respect to wall decay, DiGiano and Zhang (2005) concluded that a zero-order overall kinetic model was well suited for describing the overall chlorine decay in a heavily tuberculated cast iron pipe, whereas, first-order overall kinetic model was found suitable for new cement-lined ductile iron (CLDI) pipe. AWWARF (1996) defines the overall chlorine decay constant during the second phase to be the sum of the first-order bulk decay constant, k_b, and the effective chlorine wall decay constant, k_w, which has been used by other researchers (e.g., Rossman et al., 2001; Hallam et al., 2002). Previous research has assumed first-order chlorine wall decay (Wable et al., 1991; Biswas et al., 1993; Rossman et al., 1994; Clark et al., 1995; Kiéné et al., 1998) and been found to be characterized by first-order kinetics (Vasconcelos et al., 1996). Vasconcelos et al. (1996) found that a zero-order wall decay kinetic reaction was effective for characterizing the wall decay, but also indicated that the first-order model might be better. This manuscript assumes the overall, bulk, and wall chlorine decay constants will be of first-order kinetics.

Relatively few studies have been conducted concerning the determination of the chlorine disappearance rate in distribution systems. These studies have been conducted either in the field or in the laboratory. Field studies are normally carried out by isolating the pipe under study from the network and by monitoring the chlorine concentration upstream and downstream. Chlorine may be injected upstream. By knowing the time of passage (retention time), the first-order decay constant in the pipe, due to both the water and pipe consumption, can be determined using Eq. (2). This constant is described as the apparent or total decay constant. Though on-site studies are considered directly applicable to the distribution system as they are performed under field conditions, large potential measurement errors are expected (Hallam et al., 2002). Laboratory studies are conducted by performing the test in pipe sections and monitoring the chlorine concentration with time. Menaia et al. (2003) studied the influence of flow velocity on chlorine consumption rate using a closed loop 120-m long, with 25-mm (1-in) diameter PVC pipe. Haas et al. (2002) described the decay of chlorine residuals in new ductile iron and PVC pipes following disinfection at levels as practiced during mains disinfection (up to 100 mg/l of chlorine). Hallam et al. (2002) performed their study on different pipe materials in situ as well as in the laboratory and claimed that the laboratory and the in situ results were similar. Rossman et al. (2001) performed tests in unlined ductile iron pipe loop to simulate field conditions. The pipe used was in service for several years and subjected to significant corrosion and biofilm buildup. A recent study was carried out by DiGiano and Zhang (2005) that investigated the effect of the velocity and water quality (corrosion rate, dissolved oxygen, and pH) on the decay rate of chlorine at the pipe wall of old cast-iron and new CLDI.

Kiéné et al. (1998) presented the relative importance of some parameters, namely, total organic carbon, and water temperature, pipe material, biofilm, and corrosion process, which are responsible for chlorine disappearance in network systems. Zhang et al. (1992) performed a field study on three pipe segments, one asbestos cement (500 mm in diameter) and two steel (700/800 and 500 mm in diameter), from the