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Validation of a simple method for predicting the disinfection performance in a flow-through contactor

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ABSTRACT

Despite its shortcomings, the T10 method introduced by the United States Environmental Protection Agency (USEPA) in 1989 is currently the method most frequently used in North America to calculate disinfection performance. Other methods (*e.g.*, the Integrated Disinfection Design Framework, IDDF) have been advanced as replacements, and more recently, the USEPA suggested the Extended T10 and Extended CSTR (Continuous Stirred-Tank Reactor) methods to improve the inactivation calculations within ozone contactors. To develop a method that fully considers the hydraulic behavior of the contactor, two models (Plug Flow with Dispersion and N-CSTR) were successfully fitted with five tracer tests results derived from four Water Treatment Plants and a pilot-scale contactor. A new method based on the N-CSTR model was defined as the Partially Segregated (Pseg) method. The predictions from all the methods mentioned were compared under conditions of poor and good hydraulic performance, low and high disinfectant decay, and different levels of inactivation. These methods were also compared with experimental results from a chlorine pilot-scale contactor used for *Escherichia coli* inactivation. The T10 and Extended T10 methods led to large over- and under-estimations. The Segregated Flow Analysis (used in the IDDF) also considerably overestimated the inactivation under high disinfectant decay. Only the Extended CSTR and Pseg methods produced realistic and conservative predictions in all cases. Finally, a simple implementation procedure of the Pseg method was suggested for calculation of disinfection performance.

1. Introduction

Over the last two decades, many North American water treatment plants (WTPs) have been forced to implement new processes to meet the increasingly stringent standards related to primary disinfection of drinking water. Furthermore, although the T10 method has often been criticized for its shortcomings, this regulatory method for evaluating disinfection performance has remained largely unchanged (Lawler and Singer, 1993; Smeets et al., 2006). Considering the importance of disinfection processes in reducing the microbial risk

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and the increased popularity of Quantitative Microbial Risk Assessment (QMRA) in achieving this goal, improved methods are clearly needed to predict disinfection performance in the water industry.

Disinfection performance depends on three main factors: (i) inactivation kinetics, (ii) disinfectant decay in water, and (iii) reactor's hydrodynamics. Several models exist to describe the inactivation kinetics that occurs in a batch reactor or a plug-flow system. The simplest, the Chick–Watson model (Chick, 1908; Watson, 1908), is often sufficient for describing experimental data and was therefore adopted by the United States Environmental Protection Agency (USEPA) in 1989. The Hom (1972) and Rational (Roy et al., 1981) models are useful when deviations from linearity are observed. The latter can be caused by many factors: heterogeneity of resistance, agglomerates of microorganisms, and turbidity. Disinfectant decay is most often described by a first-order reaction with an immediate demand (due to notably fast reactions of the disinfectant with certain compounds). The Chick–Watson model can be easily modified to account for this phenomenon but does not consider the reactor hydrodynamics. Consequently, the USEPA has developed the concept of CT10 with the goal of including a simplified technique for assessing the impact of hydraulics. However, this method is known to underestimate (typically for low levels of inactivation) or overestimate (typically for high levels of inactivation) inactivation (Lev and Regli, 1992; Smeets et al., 2006). In recent guidance developed for the LT2SWTR (2010), the USEPA suggested two alternative methodologies for calculating the disinfection performance in full-scale ozone contactors. The first methodology, known as the Extended T10 method, is also based on the concept of CT10 but uses an interpolated disinfectant concentration to calculate the inactivation in each chamber. The second method, referred to as the Extended CSTR method, assumes that each contactor chamber exhibits hydraulic behavior equivalent to that of a single Continuous Stirred-Tank Reactor (CSTR).

In real contactors, the macroscopic hydraulic behavior of the flow (*i.e.*, the presence of short-circuiting or stagnant zones) is depicted by the Residence Time Distribution (RTD) obtained from a tracer test. Because the experimental results are usually not sufficiently smooth to be directly applied in the inactivation calculations, hydraulic models are frequently employed to fit the tracer results and provide continuous curves. These models further allow characterization of the hydraulic performance using specific parameters that are useful for comparing the performance at different flows or between different contactors. Many reactor models (Fogler, 2006; Haas et al., 1997; Levenspiel, 1999; Martin-Dominguez et al., 2005) have been proposed to describe this macroscopic behavior (known as macro-mixing). The most common models are the Plug Flow with Dispersion model (PFD), the Continuous-Stirred Tank Reactors in-series model (N-CSTR, where N refers to the number of CSTRs in series) and the Compartment model (Levenspiel, 1999). In comparisons, the latter requires more intimate knowledge of the hydraulic phenomena occurring inside the reactor and involves a greater number of parameters. In addition to macro-mixing, the microscopic state of mixing (*i.e.,* the level of mixing between molecules of different ages based on the time spent in the reactor) is required to fully characterize the hydrodynamics inside the contactor. Two extreme models are available to describe the degree of microscopic mixing (Fogler, 2006): the fully segregated model (or Segregated Flow Analysis, SFA), which is employed in the Integrated Disinfection Design Framework approach (IDDF) proposed by Bellamy et al. (1998), and the maximum mixedness model (or Micro-Mixing Analysis, MMA). These models will be fully explained in the following section.

As an alternative to the previously described models, several studies (Greene et al., 2006; Wols et al., 2010) have proposed the use of Computational Fluid Dynamics (CFD) to accurately simulate the hydraulic behavior of a reactor and its performance for disinfection. This method is difficult to implement and is often too expensive to be routinely implemented in small water systems. Nevertheless, CFD is a useful tool, especially for large design projects, because it allows testing of various reactor configurations. The previous models are more similar to a "black box" approach but are more suitable for wide-scale application. However, the literature does not currently offer definitive recommendations for the choice of hydraulic model that best describes the reactor hydraulics and the impact of this decision on the predicted microbial inactivation, more importantly. Because the choice of model used to describe the different phenomena (hydraulic, kinetic, etc.) occurring inside a reactor has a significant impact on the predicted disinfection performance (Ducoste et al., 2001; Greene et al., 2006; Haas et al., 1997), additional research is required in this domain. Moreover, validation of the predicted reactor performance has rarely been realized. Smeets et al. (2006) compared predictions from the T10 and CSTR methods to *Escherichia coli* inactivation and observed that both methods led to huge overestimations. Earlier, Haas et al. (1998) used SFA with the Hom model to predict the inactivation of three microorganisms (*E. coli*, MS2 coliphage and *Giardia*) using three disinfectants (ozone, chlorine and monochloramine) in two water matrices and compared their predictions with experimental results. More recently, Kim et al. (2002) and Tang et al. (2005) applied the Axial Dispersion Reactor (ADR) model to contactors with ozone diffusers and compared their predictions with the measured *Cryptosporidium* inactivation. None of those models perfectly fit the experimental data, and the closest performers were too sophisticated to be easily implemented at the WTPs for on-line inactivation calculations.

The complexity of disinfection performance evaluation has led to extreme simplifications or the development of highly sophisticated methods. Our final objective is to propose a simple and reliable method for predicting the performance of reactive contactors (*i.e.,* contactors which are only used to provide contact time with a residual disinfectant). Tracer studies originating from four full-scale plants and one lab-scale reactor were first used to compare the applicability of the N-CSTR versus PFD models. In a second step, we compared the predictions from several alternative disinfection methods (T10, Extended T10, Extended CSTR, MMA, SFA, Partially Segregated) under different hydraulic and disinfectant decay conditions. Finally, we evaluated the performance of these methods in predicting the inactivation of *E. coli* by chlorine in a lab-scale contactor.