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Research paper

Flow, transport and disinfection performance in small- and full-scale contact tanks

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Abstract

The hydrodynamics and mixing processes in small- and full-scale baffled disinfection tanks are studied experimentally and numerically. Velocity and tracer transport measurements are carried out to quantify the hydrodynamics and to obtain reliable data used to validate a three-dimensional computational fluid dynamics (CFD) model. The flow in the tank under investigation is extensively three-dimensional due to the existing inlet condition of the tank, resulting in short-circuiting and internal recirculation, particularly in the first three compartments. Near the inlet the tracer residence time distribution curve analysis and Hydraulic Efficiency Indicators (HEIs) suggest poor disinfection performance. Further away from the inlet, the flow recovers to a two-dimensional flow and the HEIs improve until the exit of the tank. The computational results demonstrate good agreement between the predicted hydrodynamics and tracer transport with the corresponding experimental data. The numerical model is then employed to investigate the effects of up-scaling of laboratory model findings to a full-scale contact tank. Despite the Froude–Reynolds conflict the full-scale contact tank exhibits similar behaviour to the small-scale tank. The effect of the tank geometry on the disinfection efficiency is demonstrated, highlighting the negative impact of flow three-dimensionality on pathogen inactivation.

Keywords: Disinfection tanks; Hydraulic efficiency; Froude–Reynolds conflict; RANS modeling; Physical model

1. Introduction

The performance of water treatment facilities has been under scrutiny following the introduction of more demanding water quality standards. A review of contact tank (CT) units, which constitute integral components of water disinfection, suggests plug flow to be the ideal hydrodynamic condition at which disinfection performance is maximized (Rauen et al., 2012; Stamou, 2002; Wang, 1995; Teixeira, 1993; Falconer and Tebbutt, 1986; Hart, 1979; Markse and Boyle, 1973). In plug flow, all elements of the fluid pass uniformly through the contact tank, i.e. in parallel paths from the inlet to the outlet sections of the tank. Plug flow conditions are ideal for the transport of disinfectants because they remain in the tank for a uniform time interval, necessary to achieve the desired disinfection. Accordingly, the hydraulic design of CTs has traditionally been based on the assumption that the contact time for all fluid elements corresponds to the theoretical hydraulic residence time (T) of a given tank (Falconer and Tebbutt, 1986), which can be estimated as $T = V/Q$, where V is the volume of the CT and Q the discharge. However, numerous CT related studies (e.g. Markse and Boyle, 1973; Falconer and Tebbutt, 1986; Falconer and Liu, 1987; Teixeira, 1993; Teixeira and Siqueira, 2008; Rauen, 2005) suggest that the flow exhibits a residence time distribution (RTD) which can be significantly different from what is dictated by plug flow. This digression can be attributed to the complex hydrodynamics including short-circuiting and recirculation zone formation

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(Kim et al., 2010a) in such tanks. Short-circuiting occurs when particles pass through a CT quicker than the theoretical hydraulic residence time. Recirculation (or dead) zones not only promote short-circuiting (because they occupy a considerable part of the volume of the tank), but they also trap solutes and particles (or pathogens), which then remain in the tank for a longer period than the theoretical hydraulic residence time. The occurrence of such flow patterns has a detrimental effect on the overall efficiency, because contact times of pathogens with the disinfectant are either too short (insufficient treatment) or too long, which can cause disinfection by-products (Kim et al., 2010b).

Research on CTs has been undertaken experimentally as well as computationally. Several experiments have been carried out employing Laser Doppler Anemometry and Acoustic Doppler Velocimetry (ADV) techniques to quantify the hydrodynamics in CTs (Teixeira, 1993; Rauen, 2005). A number of experiments have also focused on the analysis of the transport characteristics using a passive tracer and measuring its residence time distribution (RTD) at the outlet of CTs (e.g. Teixeira and Rauen, 2013; Rauen, 2005; Teixeira, 1993; Thayanity, 1984; Hart and Vogiatzis, 1982; Hart, 1979; Trussell and Chao, 1977; Markse and Boyle, 1973; Kim et al., 2010b). The shape of the tracer RTD curves can provide an insight into the hydrodynamic conditions, as explained by Levenspiel (1999) and Peplinski and Ducoste (2002).

Computational Fluid Dynamics (CFD) techniques have been implemented widely to simulate flow conditions and mixing processes during CT operation (e.g. Zhang et al., 2013; Wols et al., 2010; Kim et al., 2010a; Wang and Falconer, 1998; Khan et al., 2006; Stamou, 2008; Gualtieri, 2007; Greene et al., 2004; Hannoun and Boulos, 1997). The further integration of disinfection kinetics into computational models for CTs remains scarce and mostly limited to 2-D approaches (Wols et al., 2010; Greene et al., 2007; Wang et al., 2003; Zhang et al., 2000; Angeloudis et al., 2014a, b). An important aspect of CFD model applications is that these should be validated, ideally by comparing numerical predictions with experimental data to assess their credibility. However, hydraulic data obtained by *in situ* experimentation is normally limited to "black-box" type tracer studies, due to difficulties in obtaining hydrodynamic or solute transport measurements inside field scale tanks. Therefore, geometrically and dynamically similar physical models of CTs have been used for research and development purposes. Such experimentation has revealed the very complex hydrodynamics in such tanks (Kim et al., 2010b), but is still limited and would benefit from further investigations.

The correlation between flow conditions in scaled models and the corresponding field scale disinfection reactors poses an additional concern, due to the Froude–Reynolds (Fr–Re) conflict, i.e. a physical scale model cannot match both the Froude and the Reynolds number, which has recently been discussed by Teixeira and Rauen (2013). Essentially, physical models are characterized by an inability to simultaneously scale both the turbulence and the decay rates, which means that model predictions will not necessarily reflect prototype conditions, and in certain situations (e.g. recirculation zones) the model predictions can erroneous. Numerical simulations, on the other hand, do not have any restrictions in terms of physical parameters and quantities, and, if carried out thoroughly, can reproduce physical (e.g. turbulence) and chemical (e.g. decay kinetics) processes at any scale (Falconer, 1990).

In this study a physical model that is dynamically scaled according to the Froude number was built in the hydraulics laboratory at Cardiff University and a complementary hydrodynamic and tracer transport experimental programme was carried out. Velocity and tracer concentration measurements were obtained using ADV equipment and fluorometers, respectively. The small-scale model was influenced by the configuration and flow conditions encountered in the real-life Embsay Chlorine Contact Tank, located in Yorkshire, UK. The objectives of the study were to:

- present accurate and reliable experimental data of the hydrodynamics and passive tracer transport characteristics in a scaled CT utilized for the validation of a 3-D numerical model;
- carry out numerical simulations of flow and transport processes of a prototype-scale version of the CT, taking into consideration the effect of the $Fr - Re$ conflict on contact tank performance; and
- examine the effects of complex flow conditions in CTs on hydraulic efficiency and disinfection performance by simulating flow regimes of varying complexity (1-D, 2-D and 3-D) under identical pathogen inactivation characteristics.

2. Research methodology

2.1. Laboratory model setup

Experimental data were acquired from a model disinfection tank, which exhibited standard features of a baffled CT, i.e. the tank was divided into a certain number of compartments through which the flow meandered due to the baffles being arranged in an alternating fashion (Fig. 1). The physical model of the CT, referred to here as CT-1, was 3.0 m long, 2.0 m wide and 1.2 m deep. Internal baffles, made out of 12 mm thick PVC sheets, were installed, dividing the tank into 8 compartments of $W_C = 0.365$ m width. The inlet was located in the northeast corner of the tank and consisted of an open channel of width W_C and depth H_I of 0.30 m, which was approximately 1/4 of the tank depth. The water level in CT-1 was controlled via a rectangular sharp crested weir, located at the outlet in the 8th compartment. Two separate experiments were carried out: 1) velocity measurements to study the hydrodynamics, and 2) tracer experiments to study the transport of a conservative scalar through the tank. The maximum flow rate consistently produced during physical model experimentation by the centrifugal pumps was $Q = 4.72$ l/s. Based on the dimensions of CT-1 and the volumetric flow rate, the theoretical residence time $T = V/Q$ was $T = 1265$s. Different