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Research article

Modelling hydrodynamics of horizontal flow steel slag filters designed to upgrade phosphorus removal in small wastewater treatment plants

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ABSTRACT

Steel slag filters, if well designed and operated, may upgrade phosphorus removal in small wastewater treatment plants such as stabilization ponds and constructed wetlands. The main objective of this study was to develop a systemic modelling approach to describe changes in the hydraulic performances and internal hydrodynamics of steel slag filters under real dynamic operating conditions. The experimental retention time distribution curves (RTD curves) determined from tracer experiments performed at different times during the first year of operation of two field-scale steel slag filters were analyzed through a three stage process. First, a statistical analysis of the RTD curves was performed to determine statistical parameters of the retention time distribution. Second, classical tanks in series (TIS) and plug flow with dispersion (PFD) models were used to obtain a first evaluation of the dispersion and mixing regime. Finally, a multi-flow path TIS model, based on the assumption of several flow paths with different hydraulic properties, is proposed to accurately describe the internal hydrodynamics. Overall, the results of this study indicate that higher CaO content, round shape, and larger grain size distribution of steel slag may promote plug-like flow rather than dispersion. The results of the multi-flow path TIS model suggest that the internal hydrodynamics of steel slag filters can be primarily described by two main flow paths: (i) a faster main flow path showing higher plug flow, followed by (ii) a slower secondary flow path showing higher dispersion. The results also showed that internal hydrodynamics may change over time as a consequence of physical-chemical phenomena occurring in the filter, including accumulation of precipitates, slag hydration and carbonation, and particle segregation.

1. Introduction

Several studies have demonstrated that the addition of separate filter units containing steel slag as reactive material can upgrade phosphorus (P) removal in small wastewater treatment plants (WWTPs) such as stabilization ponds and constructed wetlands (CWs) (Vohla et al., 2011). The main mechanism of P removal is related to dissolution of CaO slag followed by precipitation of Ca-P and the accumulation of Ca-P precipitates in the filters (Claveau-Mallet et al., 2012; Barca et al., 2014). However, most of these experiments were performed at laboratory scale under controlled temperature conditions and using synthetic P solutions, and only a few field-scale experiments have been conducted under real operating conditions (Shilton et al., 2006; Lee et al., 2010; Barca et al., 2013). There is therefore a lack of data in the literature concerning the long term hydraulic and treatment performances of full-scale systems.

The hydraulic performances of filter units are usually evaluated by analyzing the experimental retention time distribution curves (RTD curves), which are often determined by measuring the tracer response at the outlet of the filters after impulse tracer injection at the filter inlet (Headley and Kadlec, 2007). Two classical hydrodynamic models are commonly used to describe the experimental RTD curves of real reactors: (i) the tanks in series model (TIS), which is based on the assumption of a series of *N* continuously stirred tank reactors (CSTR) of the same volume, and (ii) the plug flow with axial dispersion model (PFD), which is based on the hypothesis of a simple convective plug flow affected by axial dispersion. Indeed, the use of the classical TIS and PFD models can provide a first evaluation of the dispersion and mixing regime in the filters

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(Chazarenc et al., 2003; Bonner et al., 2017).

However, several authors have shown that the classical TIS and PFD models often do not accurately accommodate high, early, multi-peaks, and long tails of experimental RTD curves (Werner and Kadlec, 2000; García et al., 2004), resulting in only rough estimation of the internal hydrodynamics of wastewater treatment filters. Moreover, it should be noted that numerous biological and physical-chemical phenomena, including biofilm growth, vegetation growth, inert accumulation, precipitation and accumulation of precipitates, and particle segregation can have a direct influence on changes in the porosity and pore size of the filters, thus affecting internal flow transport patterns and modifying internal hydrodynamics (Maloszewski et al., 2006; Suliman et al., 2006; Ríos et al., 2009; Samsó et al., 2016). In addition, most of these phenomena can be affected by changes in temperature and/or organic and inorganic loads (Muñoz et al., 2006; Rizzo et al., 2014). Consequently, there is a need to develop more complex dynamic models to better describe the changes in internal hydrodynamics under real operating conditions (Kumar and Zhao, 2011; Nivala et al., 2012; Meyer et al., 2015). A wide range of more complex models, including TIS with delay, TIS with exchange zones, multi-flow path PFD, and/or networks of TIS and PFD, have been proposed to describe the experimental RTD curves of wastewater treatment filters (Werner and Kadlec, 2000; García et al., 2004; Maloszewski et al., 2006; Zeng et al., 2013).

The main objective of this study was to develop a systemic modelling approach to describe changes in the hydraulic performances and internal hydrodynamics of steel slag filters under real operating conditions. Two field-scale steel slag filters, one filled with electric arc furnace slag (EAF filter), the other filled with basic oxygen furnace slag (BOF filter), were designed to treat the effluent of a CW. The design of the filters and the experimental results are detailed in Barca et al. (2013). Tracer experiments were conducted at different times during the first year of operation, and the experimental RTD curves were plotted. Filter hydrodynamics and P removal kinetics had already been modelled using a plug flow with dead volume model and a first order kinetic equation (Barca et al., 2013). In the present study, the experimental RTD curves were further examined in order to build a more complex dynamic model to describe the changes in the internal flow patterns.

A systemic modelling approach was used involving knowledge of chemical reactor engineering applied at three different scales of investigation. First, a statistical analysis of the experimental RTD curves was carried out to determine statistical parameters including the mean retention time, the variance of the distribution, and the hydraulic efficiency of the filters. Second, classical TIS and PFD models were used to obtain a preliminary evaluation of the dispersion and mixing regime, and to identify the type of model that best describes the experimental RTD curves. Finally, a multi-flow path TIS model, based on the assumption of several flow paths with different hydraulic properties, was developed to describe changes in internal hydrodynamics and flow patterns.

The results of this study provide useful information to understand changes in the hydraulic performances of steel slag filters in real operation mode. Knowledge and understanding of hydraulic behavior under real operating conditions is indispensable to improve the design and operation of the filter system.

2. Material and methods

2.1. Filter design and operation

Two field-scale steel slag filters each with a total volume of 6 m^3 (length 5.7 m, width 2.1 m, height 0.5 m) were designed to upgrade P removal in a municipal wastewater treatment CW (*La Motte d'Aigues*, France, 1050 people equivalent (p.e.), 150 L/(p.e. *d)). One of the filters was filled with EAF slag (EAF filter), the other with BOF slag (BOF filter). Fig. S1 shows the grain size distribution of the steel slag used to fill the filters (supplementary material). The granular range 20–40 mm represented 96.8% and 77.9% of the total weight of EAF and BOF slag, respectively. The initial filter porosity of both filters was about 0.5, thus resulting in an initial void volume of about 3 m^3 for each filter.

The steel slag filters were fed with a fraction (2–4%) of the effluent from the CW and operated according to a horizontal subsurface flow and batch loads (24 batches/day) to simulate typical CW-feed. During the first nine weeks of operation, the volume of each batch load was calibrated to 120 L, thus leading to a theoretical hydraulic retention time based on the initial void volume (HRTv) of 24 h. The HRTv was then increased to 48 h after nine weeks (week 9) of operation to evaluate the effect of HRTv on P removal. Further details on the design and operation of the filter, as well as the main results of P removal performances, are given in a previous research paper (Barca et al., 2013).

2.2. Tracer experiments

Tracer experiments were performed in weeks 1 (Sept. 25–29, 2010), 9 (Nov. 22–25, 2010), 22 (Feb. 21–25, 2011), and 29 (Apr. 11–14, 2011) of operation to evaluate the hydraulic performances of the filters and changes over time. The HRTv was set to 24 h during each tracer test to compare the results of the different experiments. Five liters of a solution of 1 g fluorescein/L were instantaneously injected at the inlet of each filter (5 g fluorescein/filter). The concentrations of outlet tracer were then monitored until more than 90% of the mass of the tracer was recovered (48 h after injection of the tracer), and the concentrations of outlet tracer were plotted as a function of time.

2.3. Statistical analysis of retention time distribution

The hydraulic retention time distribution function $E(t)$ (1/h) was obtained from the experimental results of the tracer experiments using equation (1), where $C(t)$ is the outlet tracer concentration (g/L) at time t (h).

$$E(t) = \frac{C(t)}{\int C(t) \cdot dt} \tag{1}$$

$E(t)$ is a probability density function that represents the fraction of water that has a retention time less than t (Levenspiel, 1999). Next, the mean retention time τ (h), which represents the average time the water remains in the filter, was obtained by equation (2).

$$\tau = \int t \cdot E(t) \cdot dt \tag{2}$$

For each experiment, the variance of the retention time distribution σ^2 (h^2) was calculated by equation (3). σ^2 is an important parameter to assess the hydraulic performance of a filter, as it can be used as statistical indicator to evaluate the dispersive processes in the filter.

$$\sigma^2 = \int (t-\tau)^2 \cdot E(t) \cdot dt \tag{3}$$

The hydraulic efficiency parameter λ (–) was calculated by equation (4), where t_P is the peak tracer concentration time (h). Hydraulic efficiency λ is usually used to evaluate both the effective volume utilization and the shape of the tracer response (García