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Hydraulic characterization of an activated sludge reactor with recycling system by tracer experiment and analytical models

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ABSTRACT

Fluid dynamic behaviour plays an important role in wastewater treatment. An efficient treatment requires the inexistence of certain hydraulic problems such as dead zones or short-circuiting flows. Residence time distribution (RTD) analysis is an excellent technique for detecting these inefficiencies. However, many wastewater treatment installations include water or sludge recycling systems, which prevent us from carrying out a conventional tracer pulse experiment to obtain the RTD curve of the installation. This paper develops an RTD analysis of an activated sludge reactor with recycling system. A tracer experiment in the reactor is carried out. Three analytical models, derived from the conventional pulse model, are proposed to obtain the RTD curve of the reactor. An analysis of the results is made, studying which model is the most suitable for each situation. This paper is useful to analyse the hydraulic efficiency of reactors with recycling systems.

1. Introduction

Biological oxidation is one of the most important processes involved in conventional wastewater treatment. It is the process by which bacteria and other types of microorganisms (biological floc) remove organic substances dissolved in the water. Activated sludge reactors (ASR) are widely used to hold biological oxidation. The combination of wastewater and biological mass is known as mixed liquor. Air or oxygen is introduced into the mixed liquor in order to enable the reduction of the organic content of the sewage by the biological floc. Sometimes, mixer impellers are used to improve the mixing performance of the activated sludge reactor. Air diffusers and impellers can account for up to 70% of the total energy consumption of a wastewater treatment plant WWTP (Yang et al., 2011). Therefore it is very important to know and optimize the processes in the activated sludge reactor, in order to save energy and guarantee an efficient treatment.

Traditionally, handbooks of wastewater biological reactors design only include models of the chemical reactions and mass transfer processes which take place in the reactor. The assumption of an ideal flow pattern (e.g. plug flow or complete mixed flow) is made, without taking into account the real fluid dynamic behaviour within the reactor. The series of activated sludge models (Henze et al., 2000) developed by the International Water Association (IWA) are the most popular models for the design and control of activated sludge systems. However, the hydrodynamics within a biological reactor is critical to the performance of the system (Levin and Gealt, 1993). An appropriate hydraulic design improves the pollutant removal efficiency, besides optimizing the treatment and reduces costs (Badkoubi et al., 1998; García et al., 2005). Residence time distribution (RTD) analysis is a good tool for characterizing the fluid dynamic performance within a reactor, capable of detecting fluid dynamic problems such as dead zones or short-circuiting flow (Metcalf and Eddy, 2004; Fogler, 1992). The RTD curve of a reactor (commonly known as E curve) is obtained by means of a tracer technique. A mass of tracer is injected instantaneously at the inlet of the reactor. The RTD curve is obtained from the concentration of tracer versus time at the outlet of the reactor. There are many analytical models for non-ideal RTD curves (e.g. dispersion model (Levenspiel, 1999), compartment model (Bello-Mendoza and

Abbreviations: ADML, Axial Dispersion Model of Levenspiel; *ASM*, Activated Sludge Models; *ASR*, Activated Sludge Reactor; *IAEA*, International Atomic Energy Agency; *ICC*, Groche's index; *IWA*, International Water Association; *ISO*, International Standards Organization; *HBP*, Hold Back Parameter; *HEI*, Hydraulic Efficiency Indicator; *HRT*, Hydraulic Retention Time; *MBR*, Membrane Bioreactor; *REC*, Mass recovery rate; *RTD*, Residence Time Distribution; *SEG*, Segregation parameter; *SSR*, Sum of Squared Residuals; *WWTP*, Wastewater Treatment Plant.

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Nomenclature

C_A	tracer concentration at sample point A (mg/l)
C_B	tracer concentration at sample point B (mg/l)
C_C	tracer concentration at sample point C (mg/l)
d	dispersion parameter in Levenspiel's equation (Eq. (11))
$D_{0.1}$	Interval between two successive occurrences of $E(\theta) = 0.1$
$D_{0.5}$	Interval between two successive occurrences of $E(\theta) = 0.5$
E	RTD curve of the reactor (s^{-1})
I	arbitrary continuous tracer flux fraction in Eq. (10) (s^{-1})
$Li+$	lithium ion
$LiCl$	lithium chloride
$\dot{m}$	air mass flow rate introduced by the diffusers (kg/h)
M	mass of tracer added in the experiment (kg)
Mo	Morril index
N	number of points considered in Eq. (1)
Q_{tot}	total flow rate (treated and recycled) (m^3/h)
Q_t	treated flow rate (m^3/h)
Q_R	recycled flow rate (m^3/h)
P	tracer fraction flux in the primary treatment (s^{-1})
r	fraction between treated and recycled flow rate
R	tracer fraction flux in the recycling system (s^{-1})
R^2	coefficient of determination
S	tracer fraction flux in the reactor outlet (s^{-1})
t	elapsed time since the tracer release (s)
t_{10}	HEI 10% arrival time.
t_{25}	HEI 25% arrival time.
t_{50}	HEI 50% arrival time.
t_{75}	HEI 75% arrival time.
t_0	average residence time in Levenspiel's equation (Eq. (7)) (s)
t_a	delay between the samples taken in B and C (*minutes*)
t_g	HEI center of mass of the RTD function.
t_i	time where the sample i was taken (*minutes*)
t_p	HEI maximum concentration arrival time.
t_{ideal}	theoretical residence time between points B and C (*minutes*)
t_{MBR}	theoretical residence time within the MBR system (*minutes*)
tot_{tracer}	total mass of tracer which has passed through the reactor outlet
$t_{SludCham}$	theoretical residence time within the sludge chamber (*minutes*)
T	length of the tracer experiment (h)
V	volume of the activated sludge reactor (m^3)
V_{active}	active volume of the activated sludge reactor (m^3)
V_{MBR}	volume of the MBR system (m^3)
$V_{SludCham}$	volume of the sludge chamber (m^3)

Greek symbols

Δt	sampling frequency of the tracer experiment (minutes)
θ	normalized residence time
π	pi number
σ	dispersion index
τ	integration time (s)

Sharrat, 1999) or tanks-in-series model (Capela et al., 2008)). Many RTD models usually use two parameters for characterising the E curve: one parameter for the location of the peak of the curve, and the other one for the shape of the RTD curve. A good methodology for quantifying the hydraulic efficiency of a reactor is to fit an analytical mathematical model to its experimental E curve. In this way, the hydraulic efficiency of the reactor is defined by means of two parameters (shape and location parameter of the E curve) (Barreira, 2011).

Another useful tool to estimate the RTD within a reactor is the Computational Fluid Dynamics (CFD). This tool is able to simulate the different fluid dynamic phenomena which occur in a reactor, since it calculates the detailed flow field within a reactor. It is possible to calculate the tracer transport within the reactor from the numerical velocity field obtained (Angeloudis et al., 2016; Stamou, 2008). Karpinska and Bridgeman (Karpinska and Bridgeman, 2016) carried out a wide review about the application of CFD to ASRs. The literature review shows that CFD is able to accurately estimate the RTD curve within an ASR for different flow regimes. In CFD, the tracer reappearance issue is not a handicap, hence the fluid dynamic conditions can be chosen, unlike the actual plants where it is not possible to delete the recycling system. One of the main advantages of CFD models is that they can estimate the RTD curve of a reactor for different configurations and conditions, whereas the scope of empirical models is more limited. It is interesting to compare the results of CFD models with experimental data in order to check the accuracy of the models, as it is done in many works of the literature review (Angeloudis et al., 2016; Zhang et al., 2016).

In CFD, the tracer reappearance issue is not a handicap, hence the fluid dynamic conditions can be chosen, unlike the actual plants where it is not possible to delete the recycling system. However, in order to ensure the validity of the numerical simulations, an experimental validation of the results should be done (Angeloudis et al., 2016).

The fluid dynamic characterization of the flow in reactors by means of RTD pulse-response techniques is well explored and common practice (Bongo Njeng et al., 2015). It was successfully applied to describe mixing regimes in a variety of WWTPs [Majewsky et al., 2011; Olivet et al., 2005: Newell et al., 1998]; being the axial dispersion model of Levenspiel (Levenspiel, 1999) the most popular. Nevertheless, most activated sludge reactors have a recycling system in order to return the sludge to the reactor. The recycling system hampers the RTD experiment, since a fraction of the tracer introduced by the pulse is reintroduced at the inlet of the reactor. Therefore the tracer concentration at the outlet does not give the E curve of the reactor, but he superposition of the E curve and the curve generated by the recycled tracer. The above mentioned works concern wastewater reactors which do not have recycling systems, or do not analyse the E curve, but the superposition curve S. Battaglia et al (Battaglia et al., 1993). developed a method to calculate he amount of tracer leaving a reactor with recycle of the effluent (superposition curve), assuming that E curve is known (direct problem). However, they do not propose a method to estimate E curve from the concentration of tracer at the reactor outlet (inverse problem). Therefore it is interesting to develop an experimental procedure to characterize the hydraulic behaviour of a reactor with recycling system (obtaining the parameters of its E