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Biological reactor retrofitting using CFD-ASM modelling

J. Climent[a], L. Basiero[b], R. Martínez-Cuenca[a], J.G. Berlanga[b], B. Julián-López[a], S. Chiva[a,*]

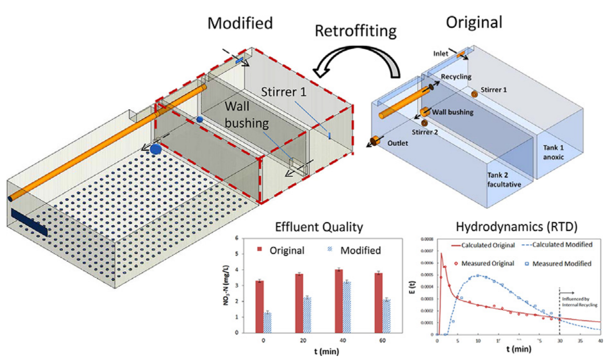
[a] UNIVERSITAT JAUME I, Department of Mechanical Engineering and Construction and Department of Inorganic and Organic Chemistry, Av. Vicent Sos Baynat, s/n, 12071 Castellón, Spain

[b] SOCIEDAD FOMENTO AGRÍCOLA CASTELLONENSE, S.A (FACSA), C/Mayor, 82-84, 12001 Castellón, Spain

HIGHLIGHTS

- CFD models were used to retrofit a full-scale tank being validated experimentally.
- A CFD virtual study was conducted to optimize the modified configuration proposed.
- RTD was demonstrated to be strongly influenced by modifications over the internal elements within the tank.
- A strategy of calculation was implemented to reduce computing time of simulations.
- CFD-ASM models allowed to evaluate the improvement of fluid behaviour and denitrification efficiency to be evaluated.

GRAPHICAL ABSTRACT



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ABSTRACT

In recent years, the interest in modelling activated sludge (AS) systems by means of Computational Fluid Dynamics (CFD) techniques has significantly increased. This work shows a successful case study combining CFD hydrodynamics and biokinetic modelling. The hydrodynamics is analysed by using the Reynolds-averaged Navier-Stokes equation for incompressible non-Newtonian fluids and SST turbulence model. Biokinetics has been included in the CFD as transport equations with source and sink terms defined by the Activated Sludge Model n°1 (ASM1). Furthermore, a strategy for reducing the computational cost while maintaining accuracy of the results of these calculations has been proposed. This strategy is based on a two-step solver configuration and the definition of a variable timestep scheme. The resulting CFD-ASM approach permits a proper evaluation of denitrification in the anoxic tanks as well as the reproduction of nitrate and readily biodegradable substrate distributions. To demonstrate the strength of the proposed CFD-ASM, it has been used to evaluate the operation of a full-scale AS system and optimize its performance through changes in the biological reactor anoxic zone. The original configuration has been retrofitted and modified after detecting intrinsic defects in the fluid behaviour within the tank. This study has been assessed by analysing hydrodynamics in detail and validating the simulation results with tracer tests and flow velocity measurements. Substantial variations on the Residence Time Distribution have been confirmed when modifying the internal elements of the tank configuration: the wall-bushing and the stirrer positioning. As a result of this work, an influential short circuiting was corrected improving hydrodynamics and increasing mean residence time, all favouring denitrification efficiency. Outcomes of this study show the benefit of CFD when applied to AS tanks.

* Corresponding author.
E-mail addresses: jcliment@uji.es (J. Climent), raul.martinez@uji.es (R. Martínez-Cuenca), julian@qio.uji.es (B. Julián-López), schiva@uji.es (S. Chiva).

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1. Introduction

The Modified Ludzack-Ettinger (MLE) biological reactor is a commonly used nutrient removal configuration, typical of municipal wastewater treatment (WWT) plants, composed of anoxic and aerobic tanks. As known, this system represents one of the simplest configurations to provide nitrification-denitrification with greater efficiency [1]. This increase in efficiency comes from two main factors: recovering lost oxygen, potentially up to 63% of the energy expended in nitrification, and alkalinity, about half of the lost through the nitrification is recovered when nitrate is used as electron acceptor of readily biodegradable organic substrate [2]. Denitrifying bacteria prefer to use molecular oxygen, but if the environment contains less than 0.3 to 0.5 mg/L of dissolved oxygen (DO), they will use the oxygen from nitrate-N molecules to oxidise carbon compounds (e.g., BOD) [3]. Hence, sufficient amounts of substrate must be ensured in anoxic conditions to carry out the denitrification process and thereby saving aeration energy consumption of the activated sludge (AS) system.

The main disadvantage of the MLE reactor configuration is that the effluent will always contain appreciable quantities of nitrate-N because nitrification occurs in the last bioreactor [4]. Consequently, the adjustment of the internal recycling ratio, which provides nitrate to the anoxic zone, is a critical operational parameter. In this case study, a common mode of operation consists of setting relatively a high internal recirculation rate in order to maintain the effluent under control. But, a high recycling ratio will strongly influence the retention time of the anoxic tank, decreasing the denitrification efficiency. Accordingly, if the mean residence time of the anoxic tank is not enough, the aerobic tank must often be controlled stopping aeration to provide (sufficient) further anoxic volume.

Mean residence time is a variable of paramount importance which should be well-known, and not assumed as the theoretical hydraulic retention time which frequently entails a poor approach. In this regard, the Residence Time Distribution (RTD) that describes the amount of time a fluid element can spend inside the reactor is commonly used as an experimental source of knowledge giving useful information about hydrodynamics and mean residence time. Though it is costly to obtain and not all RTD analytical methods provide information about short-circuiting flow or dead zones when large-volume tanks are examined [5], RTD allows quantitative measurement of mixing, and what is more important the determination of the potential for pollutant removal [6]. It is possible to obtain crucial hydrodynamic information of AS systems from Computational Fluid Dynamics CFD tools provide deep knowledge of the fluid behaviour [7]. As shown in this study, CFD techniques, CFD techniques allow the shape of the RTD curve to be analysed and modified, changing the internal elements within the tank [8]. The literature offers numerous examples of CFD tracer studies to reproduce the fluid pattern and calculate mean residence time, dead volume, mixing, short-circuiting, etc., which must be validated experimentally mainly by means of RTD, fluid velocity profiles [6–9], and even with reactive tracers [11].

Several commercial packages with different level of complexity are available for modelling WWT processes. Design and operation are frequently based on ASM [12] which are generally implemented with ideal hydraulic tank-in-series models. Nevertheless, the hydrodynamics definitely effects the efficiency of the pollution abatement [13,14]. In order to obtain a more accurate approach, hydrodynamic effects can be modelled by means of CFD, and ASM can be maintained to reproduce the nutrient removal process. Thus, to perform the simulations, it is possible to incorporate the ASM equations in the CFD code [15]. The usual solving strategy is based on two steps; in the first step the hydrodynamics is solved, and in the second step, the ASM model is solved from the velocity field (as a known variable) as a convection-diffusion problem for a set of transport equations, one for each species, where ASM terms are included as sources [14,16–18].

Authors agreed that successful modelling of the hydrodynamics facilitates the development of a complete model [16,18]. The most powerful use of the CFD is to simulate integrated physical, chemical and/or biological processes involved in WWT design and operation, but to date, it should be understood as a supportive tool for unit process design and troubleshooting [19,20].

In this paper, the authors want to exhibit the use of CFD to model a real bioreactor with malfunctions and its validation against experimental measurements. The results obtained by the validated model have been analysed and a new improved design has been developed using CFD. That new design was performed in the real WWTP, and further and more detailed experimental data were obtained to check the proposed modification and the CFD model itself.

This study deals with a faulty hydrodynamic performance of the biological reactor, which is the consequence of an influential short-circuiting detected in its design configuration (Original configuration). This direct flow between the wall-bushings, which were located facing each other, short-circuited the current flux in the second anoxic tank. In order to improve the performance, a new configuration (Modified configuration) was proposed by changing the locations of the wall-bushing and the stirrer as indicated in Fig. 2.

The outline of this work was divided into three different steps (Fig. 1). The two symmetrical wastewater treatment lanes (WWTL1, WWTL2) of the MLE bioreactor (Fig. 2) were used to carry out this study. Firstly, a CFD model (L1CFDo) was developed to study hydrodynamics in the Original configuration of WWTL1 (WWTL1o), validated experimentally by means of tracer tests (I). Secondly, the CFD model was used to perform improvements in the fluid behaviour over WWTL1 (L1CFDmod), which was eventually retrofitted. After the full-scale modifications in WWTL1, the modified configuration (WWTL1mod) was validated using tracer tests and velocity measurements (II). Finally, the CFD-ASM1 model for each configuration was developed calculating differences in denitrification performance, which were validated experimentally comparing WWTL1mod and WWTL2 (Original) (III).

As a result from this study, we demonstrate that the retrofitted configuration WWTL1 (WWTL1mod) provides an effluent with higher quality compared with the unchanged WWTL2.

2. Materials & methods

The description of the reactor has a critical importance to obtain representative process dynamics when modelling the effect of local hydrodynamic phenomena on biochemical reactions [16]. This section starts with a full description of the biological reactor under inspection and introduces the proposed retrofitting configuration. Then, the experimental techniques used for model validations are presented along with the various locations at which data were acquired. Finally, the (novel) implementation of the combined CFD-ASM1 model is briefly described.

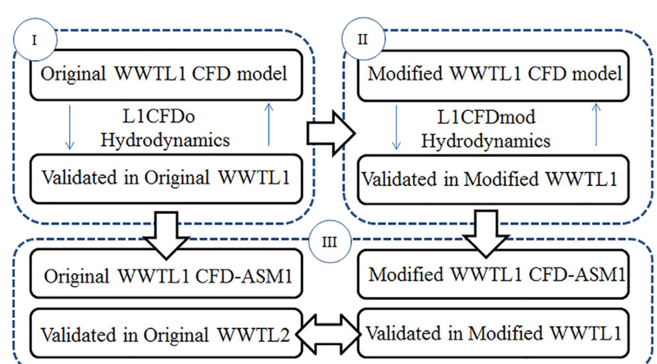

Fig. 1. General outline of the study.