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Investigation of hydrodynamic non-idealities in a pilot-scale pond bioreactor

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ABSTRACT

Pond-type reactors are widely used in biological wastewater treatment in view of their simplicity and low cost of construction. The knowledge of an approximate hydrodynamic behavior can contribute to the rational design of such operation. Thus, the aim of this work is to investigate, in a pilot scale pond bioreactor, the non-ideality through residence time distribution (RTD) technique and validation of a model for the homogeneous phase material balance. Experimental runs were carried out using the pulse injection technique of methylene blue tracer at constant water flow rate. The pilot-scale reactor constructed with a typical geometry design of those employed in animal waste treatment in southern Brazil. Residence time of 3, 6, and 9 days and a height/width ratio geometry parameter (H/D) of 0.25 and 0.18 were adopted. For each run normalized RTD functions and their moments (average residence time, variance and asymmetry) were evaluated. Variance analysis shows equivalent hydrodynamic behavior in the parameter range employed. To describe the non-idealities, we theorized several dimensionless RTD function models using a series of CSTRs (classified as conventional, bypass and recycle).The models were adjusted to the experimental data by non-linear regression and evaluated by the successive calculation method using the moments of RTD. The best model found is the representation of the pond reactor as two CSTRs in series with different volumes (first reactor with 91.5% of useful volume) and presence of dead zones (useful volume 84.9% of real volume).

1. Introduction

Pond-type reactors are widely used in biological wastewater treatment in view of the simplicity and low cost. A rational pond design should take into account the kinetics of the bioreaction taking place, as well as the hydrodynamics of the material in the pond. The pond geometrical parameters are similar in anaerobic and aerobic operations, but the presence of mixers in aerated lagoons alters the standard of mixing. Stabilization ponds are associated with anaerobic lagoons, facultative and maturation ponds and are used in municipal and industrial wastewater plants and for animal manure methane fermentation (anaerobic digestion) in rural areas. These are typical in tropical and subtropical regions of Brazil.

The standard of mixing represents hydrodynamic non-idealities associated with several features, including geometrical configuration, which can cause the formation of dead zones, velocity profiles, bypassing, internal recirculation, parallel paths, and preferential paths, among others. The classical method for measurement involves the injection of a tracer to the continuous reactor at a constant flow rate, which aids determination of the Residence Time Distribution (RTD). This technique can be employed for various system types, including the wetlands hydrodynamics [1], biofilters [2,3], hydrologic systems [4], sewage treatment [5], traditional and modified anaerobic baffled reactors [6,7], UASB reactor [8].

To describe the hydrodynamic non-idealities it is convenient to use a representative model based on experimental RTD data. In a pond-type reactor the dispersed flow model is the most commonly employed [9–13]; however, the application of this model coupled with kinetic rate law, even in steady-state conditions, does not permits the attainment of an analytical solution (except for zero or first-order reactions). This perhaps is the most limiting factor to the application of these models in the rational design of real reactors.

The combination or modification of ideal reactors, mainly Continuous Stirred Tank Reactors (CSTR), can be considered as a simpler class of non-ideal model and has been used in several works [1,14–17], including fields of sanitary engineering [5,18,19]. The use of such models provides a solution in steady state conditions by one, or a system of, linear or non-linear equations.

The objective of this work is to determine a hydrodynamics non-idealities model, considering homogeneous phase, in a typical pond-type reactor using RTD measured in a prototype, for the residence time between 3 and 9 days and a geometrical parameter height/width ratio

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(H/D) between 0.25 and 0.18. We tested models with combined or modified CSTR reactors classified as conventional and by-pass models, recycle models and interchanged model. Theoretical RTD functions for each model, as well as expressions for RTD properties, were developed. A methodology for model analysis − based on experimental properties versus theoretical RTD properties was employed for the first time. The final decision regarding the best model was based on non-linear regression adjustment characterized by the determination coefficient. The investigation, however, is limited to a situation of homogeneous flow. Therefore does not consider suspended and floating substances, others geometrical relations, and scale.

2. Theory elements and non-idealities models development

2.1. Measure of (dimensionless) RTD function

The RTD function (or exit-age distribution function), $E(t)$ (T^{-1}), represents the fraction of the material per unit time that has a certain residence time in a reactor environment. It is representative of the mixing characteristics that occur in a reactor.

For experimental measurement of $E(t)$ the main techniques are pulse and step injections of a tracer input to a continuous reactor at constant flow and the quantification of concentration, C (ML^{-3}), in the effluent stream with time, t (T). The tracer should be easily detectable, inert in the system, physically similar to the reagent mixture and must not adsorb in components of the reactor. From the tracer concentration profile for pulse technique, the RTD function is evaluated by Eq. (1) [16,20].

$$E(t) = \frac{C(t)}{\int_0^{\infty} C(t)\, dt} \tag{1}$$

For reactor projects are common to use the residence time, τ (T), defined as the ratio of the reactor volume, V (L^3) and the volumetric flow, υ_0 (L^3T^{-1}): $\tau \equiv V/\upsilon_0$. In engineering applications using the RTD results, it is more common the use dimensionless parameters, that can be used for any scale situation. Dimensionless time, θ, is defined by Eq. (2).

$$\theta \equiv \frac{t}{\tau} \tag{2}$$

Hence, a normalized RTD function, $E_\theta(\theta)$ (dimensionless), can be defined according to Eq. (3) [16].

$$E_\theta(\theta) \equiv \tau\, E(t) \tag{3}$$

2.2. Characteristics of dimensionless RTD

For each RTD function, some proprieties that characterize the hydrodynamic behavior (standard of mixing) can be evaluated, including average residence time, variance, and asymmetry parameters. The first moment of the normalized RTD function is the normalized average residence time, θ_m. It is computed as a weighted mean time of the RTD function. If no dead zone is present in the reactor, the mean residence time can be proved as equal to the projected residence time, or $\theta_m = 1$. This parameter of the distribution can be evaluated by Eq. (4) [16].

$$\theta_m = \int_0^{\infty} \theta\, E_\theta(\theta)\, d\theta \tag{4}$$

To evaluate the dispersion of the residence time distribution around θ_m, it is common to adopt the variance (second moment of RTD) that, in normalized form ($\sigma_\theta{}^2$), can be obtained by Eq. (5) [16]. The behavior of this parameter can be shown by analyzing the plug flow, when $\sigma_\theta{}^2 = 0$, or, on the other hand, it can be proven that $\sigma_\theta{}^2 = 1$ for ideal CSTR.

$$\sigma_\theta{}^2 = \int_0^{\infty} (\theta - \theta_m)^2\, E_\theta(\theta)\, d\theta \tag{5}$$

The third moment of the RTD is the asymmetry of the distribution, defined in dimensionless form ($s_\theta{}^3$) by Eq. (6). The asymmetry parameter provides an indication of the extent of the tail of the distribution. In reactor analyses, larger $s_\theta{}^3$ values can indicate hydrodynamic behavior close to CSTR or CSTR configuration. Smaller asymmetry parameters values can be interpreted as a mixing standard closer to plug-flow.

$$s_\theta{}^3 = \frac{1}{\sigma_\theta^{3/2}} \int_0^{\infty} (\theta - \theta_m)^3\, E_\theta(\theta)\, d\theta \tag{6}$$

2.3. Non-ideal models: comments and development

Real reactors do not always have a standard of mixing similar to ideal representations, such as the perfect mixing in CSTRs or plug-flow in PFR reactors. For pond-type bioreactors the non-idealities are associated with several aspects: the geometrical configuration/hydrodynamic, which can cause the formation of dead zones, velocities profiles, by-passing, internal recirculation, parallel paths, and preferential paths; the sediment deposition, which can decrease the useful volume, among others.

The RTD function can be used directly to provide the conversion in a certain real reactor, but it can also be used for adjusting of an appropriate non-idealities model. Non-idealities models normally employ information about flow patterns and/or different configurations and/or modifications of ideal reactors [16].

Perhaps the most common class of models used to establish the standard of mixing (hydrodynamic non-idealities) in ponds (anaerobic, facultative and maturation) and aerated lagoons is the dispersed flow model [10–13,21]. This model can describe situations from ideal plug-flow to completely mixed conditions and requires only one parameter: the Peclet number. The validation (adjustment) of this model can be accomplished by residence time distribution experiments. By this means, the transient one-dimension continuity equation (an elliptic second-order linear partial differential equation) should be solved with appropriate initial-boundary conditions. Three different sets of boundaries conditions can be established, referred to by Fogler [16] and Nameche and Vasel [10,21] as: closed to diffusion (or closed–closed vessel, first proposed by Danckwerts [22]); semi-open to diffusion; or open to diffusion (open-open). A Peclet parameter for each model is easily obtained from the relation with the distribution proprieties: variance and mean residence time [10,16,21], or by non-linear adjustment. The Peclet parameter of the dispersed flow model can also be obtained from continuous reaction system data with a well know reaction kinetic.

However, the solution of the governing equation in dispersed flow models coupled with kinetic of bioreaction in a steady state allows an analytical solution only for the simple zero or first-order kinetic. This is perhaps the most limiting factor to the application of this model in the rational design of real reactors. For first-order reactions under closed–closed boundary conditions, the equation to describe the concentration is known as the Danckwerts [22] or Wehner and Wilhelm [23] solution.

Other methods applied for the determination of non-idealities are based on computational fluid dynamic numeric simulations [18,24–27]. Normally these are applied for analysis of a specific system, generating results of RTD function, which aims to improve the design and/or operational conditions. Results can also be used to establish macroscopic non-ideal models.

The combination or modification of ideal reactors can be considered to produce an additional class of non-ideal models. Most widely used is the tank-in-series model. Combinations of ideal reactors, using by-pass