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Chemical Engineering Journal 140 (2008) 521–528

Chemical Engineering Journal

www.elsevier.com/locate/cej

A fundamental analysis of continuous flow bioreactor models and membrane reactor models to process industrial wastewaters

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Received 7 August 2007; received in revised form 25 November 2007; accepted 27 November 2007

Abstract

We analyse the steady-state treatment of industrial wastewaters in a continuous flow bioreactor and in an idealised continuous flow membrane reactor. The reaction is assumed to be governed by Contois growth kinetics, which is often used to model the growth of biomass in wastewaters containing biodegradable organic materials. We show that a flow reactor with idealised recycle has the same performance as an idealised membrane reactor and that the performance of a non-idealised membrane reactor is identical to an appropriately defined continuous flow bioreactor with non-idealised recycle. The performance of all three reactor types can therefore be obtained by analysing a flow reactor with recycle. The steady-states of the model are found and their stability determined as a function of the residence time. The performance of the reactor at large residence times is obtained. In the limit as the residence time becomes very large, all three reactor configurations have identical performances. Thus the main advantage of using a membrane reactor, or a flow reactor with recycle, for the treatment of industrial wastewaters and slurries is to improve the performance at low residence times.

Keywords: Activated sludge; Bioreactor; Chemostat; Contois growth kinetics; Membrane reactor; Modelling; Recycling; Slurries; Stirred tank; Wastewater; Water treatment

1. Introduction

A continuous flow bioreactor is a well-stirred vessel containing microorganisms (X) through which a substrate (S) flows at a continuous rate. The microorganisms grow in the vessel through the consumption of the substrate to produce more microorganisms and products (P). The products will typically contain carbon dioxide, water and other species, including biological compounds, specific to the process under consideration. The nature of these products is unimportant in this study, as they do not affect the results presented here. Unused substrate, microorganisms, and the product flow out of the reactor. In the treatment of industrial wastewaters, a reactor configuration of this description is also known as an 'aeration only complete mixing activated sludge system' or a 'conventional sewage sludge digester'. In a bioreactor with recycle the effluent emerging from the reactor is fed into a settling unit. Microorganisms settle to the bottom of the tank, from where they are recycled into the reactor vessel. As a consequence of settling the concentration of microorganisms leaving the settling unit in the recycle stream is higher than that entering it from the biological reactor. The settling of the microorganisms greatly reduces their concentration in the effluent leaving the settling unit, producing a cleaner effluent stream. Recycle enables a higher concentration of microorganisms to be maintained in the bioreactor, which allows the reactor to run at much greater flow-rates and increases its efficiency. This process is illustrated in Fig. 1.

In the treatment of industrial wastewaters, recycle is also known as 'sludge return' and a continuous flow bioreactor operating with recycle is known as the 'activated sludge process'. A practical consideration is to reduce both the substrate concentration and the microorganism concentration in the effluent. This is achieved by having a separate wasting of microorganisms after the reaction mixture has passed through the settling

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1385-8947/$ – see front matter
doi:10.1016/j.cej.2007.11.035

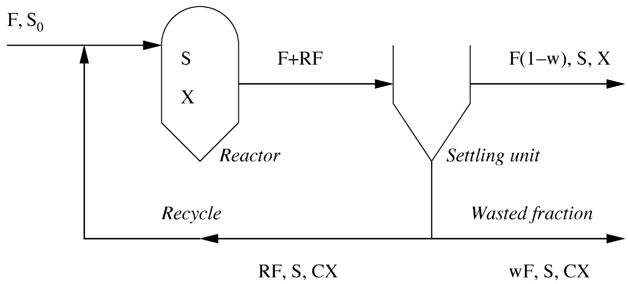

Fig. 1. A bioreactor with recycle and separate wasting of biomass. Nomenclature: C, the recycle concentration factor; F, flowrate through the reactor; R, recycle ratio; S_0, concentration of substrate in the feed; S, substrate concentration in the reactor; X, cellmass concentration in the reactor; and w fraction of sludge wasted after passing through the settling unit.

unit, $0 < w < 1$ in Fig. 1. This produces an effluent with lower suspended solids.

Flow reactors have long been used in the treatment of industrial wastewaters, where the objective is to reduce the concentration of a soluble organic substrate. One advantage that they offer over other types of reactors is that they produce a greater operational stability in response to toxic or shock loads [1]. This is because mixing dilutes spikes in toxicity levels (‘shock loads’) across the whole of the reactor volume. A flow-reactor with recycle, augmented by a term representing death of microorganisms, is the simplest model for the biological treatment of industrial wastewaters [2].

Bioreactors sometimes employ a permeable membrane, such as a microfiltration membrane, to physically retain microorganisms inside the reactor. The higher concentrations of microorganisms obtained leads to greater pollutant removal, allowing for a more rapid and efficient process. In ultrafiltration membrane reactors the membrane also retains solids and high-molecular weight compounds that are found in the effluent from a conventional activated sludge reactor. Thus the quality of the water delivered by a membrane reactor can be significantly cleaner than that emerging from conventional reactors. Due to these advantages, membrane reactors have increasingly been used as key elements of advanced wastewater processing schemes. The higher quality water that they can produce and their compactness compared to conventional reactors make membrane reactors particularly suitable for the development of domestic wastewater treatment facilities in urban areas [3]. Although there exists detailed models for wastewater treatment kinetics, such as the IWA ASM model [4], we use a simple two-variable kinetic model in which the degradation of a biodegradable organic material is given by the Contois expression [5]. This choice is motivated by the experimental investigations detailed in Section 1.1 in which this kinetic model was found to accurately describe the processing of certain industrial wastewaters.

The objectives of the current paper are:

- to provide a more detailed investigation of the steady-state behaviour of this process model than previously undertaken;
- to extend the process model to include recycle;
- to consider the restriction of the process to an idealised membrane reactor.

Our analysis will be useful in future experimental studies in which the underlying process kinetics are given by the Contois growth rate expression. It also provides the baseline for investigations into the performance improvement that can be achieved in such systems through the use of reactor cascades.

1.1. Contois growth kinetics

Many industrial processes, particularly in the food industry, produce slurries or wastewaters containing high concentrations of biodegradable organic materials (pollutants). For example, the production of slurries is a feature of large pig and poultry farms and other operations involving animal production. Before the slurry/wastewater can be discharged the pollutant concentration must be reduced. One way to achieve a reduction in the concentration of a biodegradable organic pollutant is to pass the wastewater through a bioreactor containing biomass which grows through consumption of the pollutant.

The Contois growth model, Eq. (3), has been used to model the aerobic degradation of wastewater originating from the industrial treatment of black olives [6], the anaerobic treatment of dairy manure [7,8], the anaerobic digestion of ice-cream wastewater [9], the anaerobic treatment of textile wastewater [10] and the aerobic biodegradation of solid municipal organic waste [11]. Anaerobic conditions are favoured for the processing of waste materials with high levels of biodegradable organic pollutants as these can be removed with low investment and operational costs [12].

The Contois growth expression has been found to model the anaerobic reduction of sulphate by a sulphate-reducing bacteria [13]. This procedure has application in the cleaning of sulphate-containing industrial effluents and in the cleaning of acid mine drainage.

Simulation dynamics based upon Contois kinetics for the hydrolysis kinetics of swine waste, sewage sludge, cattle manure and cellulose have been found to fit experimental data [14]. The Contois growth rate has also been used as a default growth-rate model in simulations of the cleaning of wastewater by microorganisms [15]. Limited theoretical investigation of a continuous flow bioreactor model using Contois kinetics has been carried out by earlier researchers [7–10,13,14]. These investigations were undertaken to aid in the analysis of experimental data and correspond to the choice of parameter values $\beta = 1$, $\gamma = 0$ and $k_d > 0$ in Eqs. (1) and (2). In [7,9,10,14] the maintenance energy was assumed to be zero ($m_s = 0$) whereas in [8,13] the maintenance energy was assumed to be non-zero ($m_s > 0$). The Contois growth model gave predictions that were in excellent agreement with experimental measurements. In some cases the Contois model was shown to give better agreement with data than other growth rate expressions [7,9,10,13]. We extend these earlier theoretical investigations, in particular we consider a flow reactor with recycle and we determine the stability of all solution branches. We note that earlier investigators assumed that the no-washout solution branch is always stable.