Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Aquacultural Engineering 34 (2006) 198–213
aquacultural engineering
www.elsevier.com/locate/aqua-online

Comparative performance of fixed-film biological filters: Application of reactor theory

Barnaby J. Watten *, Philip L. Sibrell

United States Geological Survey, Leetown Science Center, 11649 Leetown Road, Kearneysville, WV 25430, USA

Received 20 December 2004; accepted 25 March 2005

Abstract

Nitrification is classified as a two-step consecutive reaction where R_1 represents the rate of formation of the intermediate product NO_2-N and R_2 represents the rate of formation of the final product NO_3-N. The relative rates of R_1 and R_2 are influenced by reactor type characterized hydraulically as plug-flow, plug-flow with dispersion and mixed-flow. We develop substrate conversion models for fixed-film biofilters operating in the first-order kinetic regime based on application of chemical reactor theory. Reactor type, inlet conditions and the biofilm kinetic constants K_i (h^{-1}) are used to predict changes in NH_4-N, NO_2-N, NO_3-N and BOD_5. The inhibiting effects of the latter on R_1 and R_2 were established based on the γ relation, e.g.:

$$\gamma = \frac{K_i}{K_{i,\max}} = \left(1 - \frac{[BOD_5]}{[BOD_{5,\max}]}\right)^N$$

where $BOD_{5,\max}$ is the concentration that causes nitrification to cease and N is a variable relating K_i to increasing BOD_5. Conversion models were incorporated in spreadsheet programs that provided steady-state concentrations of nitrogen and BOD_5 at several points in a recirculating aquaculture system operating with input values for fish feed rate, reactor volume, microscreen performance, make-up and recirculating flow rates. When rate constants are standardized, spreadsheet use demonstrates plug-flow reactors provide higher rates of R_1 and R_2 than mixed-flow reactors thereby reducing volume requirements for target concentrations of NH_4-N and NO_2-N. The benefit provided by the plug-flow reactor varies with hydraulic residence time t as well as the effective vessel dispersion number, $D/\mu L$. Both reactor types are capable of providing net increases in NO_2-N during treatment but the rate of decrease in the mixed-flow case falls well behind that predicted for plug-flow operation. We show the potential for a positive net change in NO_2-N increases with decreases in the dimensionless ratios $K_{2,(R_2)}/K_{1,(R_1)}$ and [NO_2-N]/[NH_4-N] and when the product $K_{1,(R_1)}t$ provides low to moderate NH_4-N conversions. Maintaining high levels of the latter reduces the effective reactor utilization rate (%) defined here as (RN_{avg}/RN_{max})100 where RN_{avg} is the mean reactive nitrogen concentration ([NH_4-N] + [NO_2-N]) within the reactor, and RN_{max} represents the feed concentration of the same. Low utilization rates provide a hedge against unexpected increases in substrate loading and reduce water pumping requirements but force use of elevated reactor volumes. Further γ effects on R_1

* Corresponding author. Tel.: +1 304 724 4425; fax: +1 304 724 4428.
E-mail addresses: barnaby_watten@usgs.gov (B.J. Watten), philip_sibrell@usgs.gov (P.L. Sibrell).

0144-8609/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.aquaeng.2005.03.006

and R_2 can be reduced through use of a tanks-in-series versus a single mixed-flow reactor configuration and by improving the solids removal efficiency of microscreen treatment.

Keywords: Modeling; Nitrification; Aquaculture; Reactor theory; Performance

1. Introduction

Fixed-film biological filters are often used to oxidize fish excretory products in recirculating aquaculture systems (RAS) so as to reduce both make-up water requirements and pollutant loads on receiving streams (Liao and Mayo, 1974; Wheaton et al., 1994; Shnel et al., 2002). Fixed-film treatment also shows potential for improving discharge quality in single pass fish culture applications (Losordo and Westers, 1994; Bergheim and Brinker, 2003). In both cases, biofilm development is encouraged within reactors designed to provide the substrate, surface area and hydrodynamic conditions necessary to maintain activity at high biomass concentrations. Active surfaces within the reactor consist of a matrix of microorganisms and extra-cellular polymers that allow for attachment to solid surfaces (Hagopian and Riley, 1998). The composition, density and thickness of the biofilm that develops, following an initial conditioning period, is influenced by site specific conditions including wastewater composition, substrate flux, biofilm growth, decay and shear losses (Rittmann and McCarty, 1980, 1981; Meunier and Williamson, 1981). Biofilms in typical aquaculture applications include autotrophic bacteria of the genus *Nitrosomonas* and *Nitrobacter* responsible for the conversion of NH_4-N to NO_3-N as well as heterotrophic bacteria capable of oxidizing organic matter, e.g., the genus *Acenitobacter* (Bullock et al., 1993). Heterotrophic bacteria exhibit a relatively high net cell yield per unit mass substrate oxidized (Rittmann and Snoeyink, 1984) which can, under high organic loading conditions, lead to inhibition or displacement of nitrifers from the biofilm matrix (Liao and Mayo, 1974; Ohashi et al., 1995; Satoh et al., 2000; Zhu and Chen, 2001). Inhibition or displacement can result in incomplete nitrification with an associated rise in NH_4-N and NO_2-N above design limits established to circumvent ammonia toxicity (Colt and Armstrong, 1981) and nitrite induced methemoglobinemia (Smith and Williams, 1974; Manthe et al., 1984). Reactor staging can be used to improve nitrification rates when treating waters with high concentrations of organic matter (Srna, 1975; Antonie, 1976; Miller and Libey, 1984; Watten et al., 1993). This configuration promotes the development of biofilms adapted specifically to wastewaters present within each successive stage, e.g., heterotrophs in initial stages and nitrifers in later stages. Additionally, staging can be used to establish fluid residence time distributions (RTD) that approximate plug-flow behavior known to provide superior substrate conversion when reaction rates are substrate limited—reaction orders > 0 (Levenspiel, 1972). Examples of fixed-film reactors designed to operate in the plug-flow mode include multi-stage RBC's (Grady and Lim, 1980; Miller and Libey, 1984), up-flow and down-flow submerged beds (Haug and McCarty, 1972; Paller, 1992; Ridha and Cruz, 2001), trickle filters (Rogers and Klemetson, 1985; Kruner and Rosenthal, 1983; Kamstra et al., 1998) and fluidized beds (Summerfelt and Cleasby, 1993; Nam et al., 2000; Sandu et al., 2002). The latter type is unique in that the solid phase (media with attached biofilm) is mixed providing a homogenous distribution of reactive surfaces and the potential for providing effluent substrate concentrations that lie below that required, on average, to maintain an active biofilm (Rittmann, 1982). The solid phase used in the alternative plug-flow filter types is fixed in position. This requirement establishes a heterogeneous biofilm along the longitudinal axis of the reactor (Haug and McCarty, 1972; Nijhof, 1995). Mixed-flow reactors are designed to operate with complete mixing in both liquid and solid phases. Examples here include the moving bed biofilter (Rusten et al., 1998; Zhu and Chen, 1999), the rotating biodrum (Rogers and Klemetson, 1985; Wheaton et al., 1994) and single stage RBC's. Mixed-flow reactors are preferred when reaction rates are not substrate limited—reaction order = 0 (Levenspiel, 1972). Biofilm reactor type must be chosen carefully given its effect on