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Comparative influential effects of mass transfer resistance in acetate-fed and glucose-fed sequential aerobic sludge blanket reactors

Hsin-Hsien Chou, Ju-Sheng Huang*, Chun-Wen Tsao, Yen-Chun Lu

Department of Environmental Engineering, Kun Shan University, Tainan City 710, Taiwan, ROC

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ABSTRACT

A laboratory study was undertaken to explore the influential effects of mass transfer resistance on overall substrate removal in acetate-fed and glucose-fed sequential aerobic sludge blanket reactors. In both reactors, solids retention time decreased with increasing OLR [2–8 kg chemical oxygen demand (COD)/m^3 d], resulting in increasing specific substrate utilization rates. The obtained kinetic parameters values (k/K_s ratio) indicated that the microbial reaction rate for acetate was higher than that for glucose. The simulated mass transfer parameter values (ϕ^2, Bi, L, and η) and substrate concentration profiles in the granule indicated that the overall substrate removal in the acetate-fed and glucose-fed reactors are intra-granular diffusion controlled, and the influential effect of intra-granular mass transfer resistance in the glucose-fed reactor is relatively greater. The simulated results also disclosed that the optimal d_p for acetate-fed and glucose-fed reactors should be no greater than 3.5 and 2.5 mm, respectively. The validated kinetic model and the obtained kinetic parameter values can be appropriately used to simulate treatment performance of the SASB reactors treating simple substrates.

1. Introduction

In recent years, sequential aerobic sludge blanket (SASB) reactors have been used for treating various kinds of wastewaters because of their ability to form biomass granules (granule diameter d_p = 0.5–4.6 mm) and to retain high biomass concentrations [X_i = 4–17 g volatile suspended solids (VSS)/L] [1–6]. The SASB reactors can effectively treat simpler substrates (e.g., acetate) and carbohydrate substrates (e.g., glucose) at an organic loading rate (OLR) of up to 15 kg COD/m^3 d, respectively [1–3,7]. The OLR of the SASB reactor is considerably higher than the conventional activated-sludge reactor (OLR = 1–3 kg COD/m^3 d), making aerobic granulation become a promising, efficient biological wastewater treatment technology.

The biomass granule is generally treated as a biocatalyst when a biofilm/granule model is formulated. The substrate is first transferred from the bulk liquid via the diffusion layer to the surface of the granule, followed by successive intra-granular mass transfer and biochemical reaction within the granule [8,9]. Thus, a biofilm/granule model (solid phase) combining with a process model (liquid phase) was commonly used to calculate the residual substrate concentration in fixed-film reactors; well-agitated batch reactors with dispersed sludge or suspended-growth culture (eliminating both external and internal mass transfer resistances) were frequently used to determine the intrinsic kinetic parameter values required in model calculation [10,8]. To comprehend the role of external and intra-granular mass transfer resistances playing in overall substrate removal in the SASB reactor, four mass transfer parameter values calculated by a validated kinetic model can be used: (1) Thiele modulus (ϕ^2; the ratio of the maximum reaction rate to the maximum internal diffusion rate), (2) Biot number (Bi; the ratio of the external mass transfer rate to the internal mass transfer rate), (3) diffusion layer thickness (L), and (4) overall effectiveness factor (η; the ratio of the observed reaction rate for substrate removal to the reaction rate which would be obtained without internal and external mass transfer resistances) [11,12].

According to Tay et al. [7], glucose-fed aerobic granules mainly consisted of coccoid bacteria in the internal part of the granule and rod-like bacteria at the granule surface (with filaments tangled together), exhibiting irregularly shaped, with folds, crevices and depressions. In contrast, rod-like bacteria were predominant in acetate-fed granules, having a compact spherical morphology. The loose filamentous matrix facilitates glucose-fed granules to sustain significantly a higher OLR than the denser and more compact acetate-fed granules, before mass transfer resistance become restrictive [7]. Nonetheless, only a little information on the influential effects of mass transfer resistance on overall substrate removal in glucose-fed and acetate-fed SASB reactors is currently available. In general, if the value of ϕ is less than 0.3 and the value of η approaches to unity, the biochemical process is regarded as reaction-controlled instead of diffusion-controlled [13]. Li and Liu [14] and Liu et al. [15] reported that a moderate change of η (for

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* Corresponding author. Tel.: +886 6 2051331; fax: +886 6 2050540.
E-mail address: huangjsd@mail.ncku.edu.tw (J.-S. Huang).

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Nomenclature

Bi, $\mathrm{Bi_j}$	Biot number (dimensionless)
d_p	average diameter of granules based on surface area (mm)
$D_{f,j}$	diffusion rate of substrate within granule (m^2/d)
$D_{w,j}$	diffusion rate of substrate in diffusion layer (m^2/d)
k, k_j	intrinsic maximum specific substrate utilization rate (mg COD/mg VSS d)
K_s, $K_{s,j}$	intrinsic half-saturation constant (mg COD/L)
L, L_j	thickness of diffusion layer (mm)
$M_{x,j}$	biomass (g VSS)
Q_i	daily flow into SASB reactor based on 4-h cycle operations (L/d)
r; r^*	radial distance from center of granule (mm; dimensionless)
Re	Reynolds number
R_j	granule radius (mm)
$S_{b,j}$	substrate concentration in bulk liquid (mg COD/L)
$S^*_{b,j}$	dimensionless substrate concentration in bulk liquid = $S_{b,j}/K_{s,j}$
Sc	Schmidt number
$S_{f,j}$	substrate concentration within granule (mg COD/L)
$S^*_{f,j}$	dimensionless substrate concentration within granule = $S_{f,j}/K_{s,j}$
$S_{i,j}$	influent substrate influent concentration (mg COD/L)
$S_{s,j}$	substrate concentration at liquid/granule interface (mg COD/L)
$S^*_{s,j}$	dimensionless substrate concentration at liquid/granule interface = $S_{s,j}/K_{s,j}$
u_s	superficial velocity (m/h)
V_R	reactor volume (L)
X_f, $X_{f,j}$	biomass density of granules (mg VSS/L)

Greek letters

ϕ, ϕ_j	Thiele modulus (dimensionless)
ε	porosity of SASB reactor (dimensionless)
υ	dynamic viscosity (m^2/s)
η, η_j	effectiveness factor (dimensionless)

Superscript

*	dimensionless

Subscripts

j	for acetate (j = a); for glucose (j = g)
a	acetate
g	glucose

acetate uptake) from 1.0 to 0.7 for aerobic granules with a granular size smaller than 0.5 mm was observed, η however decreased rapidly to 0.1 with a further increase in granule diameter to 1.0 mm. This implied that the mass transfer resistance plays an important role in the overall substrate removal in reactors. Liu et al. [15] also presented a η (for acetate uptake)-Thiele modulus (ϕ) diagram, showing that the biochemical process is reaction-controlled for granules with a diameter of smaller than 0.7 mm and diffusion-controlled for a granule diameter larger than 0.7 mm.

The principal objective of this study was to explore the influential effects of mass transfer resistance on the overall substrate removal in the acetate-fed and glucose-fed SASB reactors. Therefore, two identical SASB reactors were respectively used to treat acetate-based and glucose-based synthetic wastewaters to generate experimental data. A kinetic model for the SASB reactor was formulated, and all intrinsic kinetic parameters required in model calculation were also evaluated. The validated model was then applied to calculate mass transfer parameter values (ϕ^2, Bi, L, and η), to simulate substrate concentration profiles in the granule, and to simulate the effect of granule size on SASB-reactor performances. Moreover in this article, granule physical characteristics are discussed as well.

2. Model formulation

2.1. Assumptions

The following assumptions are made for the formulation of a kinetic model that can be used for simulating variations in substrate residual concentration with different operating conditions in the SASB reactor:

1. The granule is spheroid-shaped.
2. The microbial growth and detachment rates are in equilibrium. Also, a steady-state granule has no net increase in mass per granule [16].
3. The mass of microbial cells in the diffusion layer (i.e., diffusing distance from the bulk fluid to the liquid-granule interface) is neglected, and Fick's law follows.
4. The complete-mix flow regime in the liquid phase of the SASB reactor is assumed to prevail because in the present study a superficial gas velocity of as high as 0.0138–0.0277 m/s did induce rigorous mixing in the reactor, resulting in a slight variation (2–3 mg COD/L) in the measured substrate concentrations along the reactor height.
5. The aerobic degradation rate of acetate and glucose (expressed as COD) follows Monod kinetics.

2.2. Solid phase

When steady state is reached in the SASB reactor, the diffusion rate of substrate from the bulk liquid to the granule equals the utilization rate of substrate. By selecting the half-saturation constant (K_s) and the granule radius (R) as a substrate characteristic concentration and a characteristic length, respectively, the solid-phase model [16,17] in dimensionless form can be derived, as shown below:

$$\frac{d^2S^*_{f,j}}{dr^{*2}} + \frac{2}{r^*}\frac{dS^*_{f,j}}{dr^*} = 9\phi_j^2\frac{S^*_{f,j}}{1+S^*_{f,j}} \qquad (j = a, g) \tag{1}$$

where

$$\phi_j^2 = \frac{k_j X_{f,j} R_j^2}{9D_{f,j}K_{s,j}} \qquad (j = a, g) \tag{2}$$

The boundary conditions for Eq. (1) are

$$\frac{dS^*_{f,j}}{dr^*} = 0 \quad \text{at} \quad r^* = 0 \quad \text{(the center of granule)} \qquad (j = a, g) \tag{3}$$

$$\frac{dS^*_{f,j}}{dr^*} = \mathrm{Bi_j}\left(S^*_{b,j} - S^*_{s,j}\right) \quad \text{at} \quad r^* = 1 \quad \text{(the surface of granule)} \qquad (j = a, g) \tag{4}$$

where

$$\mathrm{Bi_j} = \frac{D_{w,j}R_j}{D_{f,j}L_j} \qquad (j = a, g) \tag{5}$$