ELSEVIER

Biochemical Engineering Journal 27 (2005) 167–178

Biochemical Engineering Journal

www.elsevier.com/locate/bej

Effects of simultaneous internal and external mass transfer and product inhibition on immobilized enzyme-catalyzed reactor

Ali E. AL-Muftah [a,*], Ibrahim M. Abu-Reesh [b]

[a] *Petroleum Engineering Department, Bahrain Petroleum Company (BAPCO), Awali, P.O. Box 25504, PETEX, Bahrain*
[b] *Department of Chemical Engineering, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia*

Received 13 February 2005; received in revised form 23 July 2005; accepted 2 August 2005

Abstract

A mathematical model has been developed for predicting the performance and simulation of a packed bed immobilized enzyme reactor performing lactose hydrolysis, which follows Michaelis–Menten kinetics with competitive product (galactose) inhibition. The performance characteristics of a packed bed immobilized enzyme reactor have been analyzed taking into account the simultaneous effects of internal and external mass transfer limitations. The model design equations are then solved by the method of weighted residuals such as Galerkin's method and orthogonal collocation on finite elements.

The effects of simultaneous internal and external mass transfer coupled with product inhibition have been studied and their effects were shown to reduce internal effectiveness factor. The effects of product inhibition have been investigated at different operating conditions correlated at different regimes using dimensionless β_{xo} (St, Bi, θ, ϕ). Product inhibition was shown to reduce substrate conversion, and to decrease effectiveness factor when $\beta_s > \beta_{xo}$; however, it increases internal effectiveness factor when $\beta_s < \beta_{xo}$. The effectiveness factor is found to be independent of product inhibition at crossover point at which β_{xo} is defined. Effects of St and Bi have been investigated at different kinetic regimes and the results show their effects have a strong dependence on kinetic parameters θ, γ (i.e. K_m/K_p) and β_{xo}. The dimensionless residence time at crossover point, β_{xo}, has been correlated with kinetic and mass transfer parameters.

Keywords: Biocatalysis; Enzyme bioreactors; Immobilisation; Immobilised enzymes; Product inhibition; Internal mass transfer

1. Introduction

Lactose is a disaccharide that occurs naturally in both human and cows milk which accounts for 40% of milk solids. It is widely used in baking and commercial infant-milk formulas. The hydrolysis of lactose, the sugar of milk to glucose and galactose has received much attention in recent years [1,2]. It is used for production of low lactose milk for consumers that suffer from lactose deficiency (70% of the world population is lactose deficient, Carrara and Rubiolo [3]). The hydrolysis product is sweeter and more soluble and biodegradable than lactose and can be used in further biotechnological processes.

The amount of lactose produced annually from whey is about 3.3 million tonnes [3]. It is produced as cheese whey, which is the liquid, separated after milk coagulation. It represents about 90% of the milk volume. The disposal of whey is considered a serious pollution problem facing dairy industry because of its high pollutant content (COD of about 70,000 ppm). Acid hydrolysis of lactose is not favorable because of color formation and fouling of ion exchange resins used in processing. A better alternative is the use of enzymatic method. Enzymatic lactose hydrolysis is carried out by adding β-galactosidase commonly known as lactase to milk, skim milk or whey to hydrolyze lactose prior to pasteurization. Lactase is commercially available and used in large-scale processes. One problem associated with the use of lactase is that complete hydrolysis is difficult to achieve because of product (galactose) inhibition and production of isomer of lactose, allolactose. Several microbial sources of

* Corresponding author.
E-mail address: ali_almuftah@bapco.net (A.E. AL-Muftah).

1369-703X/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.bej.2005.08.026

Nomenclature

A	external surface of support per unit volume of reactor
C_P	product concentration in an immobilized enzyme support particle
$\langle C_P \rangle$	average product concentration in an immobilized enzyme support particle
C_{Pb}	product concentration in the bulk liquid (reactor phase)
C_{Pb0}, C_{P0}	product concentration at reactor inlet
C_S	substrate concentration in an immobilized enzyme support particle
$\langle C_S \rangle$	average substrate concentration in an immobilized enzyme support particle
C_{Sb}	substrate concentration in the bulk liquid
C_{Sb0}, C_{S0}	substrate concentration at reactor inlet
D_{Sp}, D_{Pp}	effective substrate and product diffusivity in an immobilized enzyme support particle
D_{Sz}, D_{Pz}	effective substrate and product axial dispersion coefficient
K_e	reaction equilibrium constant
K_L	mass transfer coefficient
K_La	volumetric mass transfer coefficient
K_{LS}, K_{LP}	mass transfer coefficient in substrate and product side, respectively
K_m	intrinsic Michaelis–Menten constant
K_p	product inhibition constant
L	length of the reactor
r	radial coordinate of distance in an immobilized enzyme support particle
$\tilde{R}_b$	dimensionless reaction rate at the surface of the spherical particles
R_P	local product production rate per unit of catalytic particle volume
$\langle R_P \rangle$	average product production rate
R_S	local substrate consumption rate per unit of catalytic particle volume
$\langle R_S \rangle$	average substrate consumption rate
t	time inside reactor
u	superfacial fluid phase velocity inside the reactor
v_{max}	maximum reaction rate per unit of catalytic particle volume
x, z	reactor radial and axial coordinate

Dimensionless variables

Bi	Biot number
Da	Damkohler number
K_E	inverse of the equilibrium constant
P	dimensionless product concentration in an immobilized enzyme support particle
$\langle P \rangle$	dimensionless average product concentration in an immobilized enzyme support particle
P_b	dimensionless product concentration in the bulk liquid
P_{b0}	dimensionless product concentration at the reactor inlet
Pe	Peclet number
$\tilde{R}$	dimensionless reaction rate in an immobilized enzyme support particle
S	dimensionless substrate concentration in an immobilized enzyme support particle
$\langle S \rangle$	dimensionless average substrate concentration in an immobilized enzyme support particle
S_b	dimensionless substrate concentration in bulk liquid
S_{b0}	dimensionless substrate concentration at reactor inlet
St	Stanton number
X	fractional substrate conversion
Y	reactor yield

Greek symbols

α_z, α_P	effective diffusivity ratio of substrate and product in axial and interparticle, respectively
β, β_s	dimensionless residence modulus
ε	reactor voidage
ϕ	Thiele modulus
γ	dimensionless inhibition modulus
η	internal effectiveness factor
η_E	external effectiveness factor
θ	dimensionless Michaelis–Menten constant
τ	dimensionless time
ξ	dimensionless radial coordinate
ζ	dimensionless axial coordinate

β-galctosidase and reactor types have been used for the purpose of economic production of low lactose milk. Lactose hydrolysis in plug flow reactor gives higher conversion compared to continuous stirred tank reactor although the latter has good mixing and lower construction cost.

1.1. Kinetics of lactose hydrolysis

Kinetics of lactose hydrolysis has been studied extensively in the literature [1,2,4]. Michaelis–Menten model with competitive product inhibition by galactose is widely used to describe the hydrolysis [1]. Different types of bioreactor [5,6] and biocatalyst [1,2,7,8] have been investigated for lactose hydrolysis.

1.2. Modeling immobilized enzyme reactor

Enzyme immobilization offers a number of advantages over enzymes in suspension. Immobilization permits the reuse of the enzyme and may provide a better environment