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NOTE

OXYGEN TRANSFER ANALYSIS IN A DUAL HOLLOW-FIBER BIOREACTOR SYSTEM

Ho Nam CHANG* and Bong Hyun CHUNG

Department of Chemical Engineering, Korea Advanced Institute of Science and Technology, P.O. Box 131, Cheongryang, Seoul, Korea

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Abstract—Oxygen transfer analysis in a dual hollow-fiber bioreactor system was carried out by simulation. Oxygen penetration depth and volumetric oxygen uptake rate were not much affected by the silicone membrane thickness and major portion of oxygen transfer resistance existed in the immobilized cell layer.

INTRODUCTION

Recently Robertson and Kim [1], and Chang and his associates [2-7] developed the dual hollow-fiber bioreactors for carrying out three phase biological reactions. These reactors are revolutionary ones capable of carrying out enzymatic reactions involving gas phase such as glucose oxidation and culturing aerobic cells efficiently. The objectives of this study is to provide the design factors of the reactor by oxygen transfer analysis.

In this study the reactor designed by Chang and his associates was adopted as a model. The detailed structure of this reactor has been already reported [2-7]. Fig. 1 (A) shows the structure of a dual hollow-fiber unit. The microbial cells grew within the space formed by the silicone tube and polypropylene (pp) hollow fibers and oxygen was supplied through the former and the medium through the latter. Fig. 1 (B) shows the simplified model of Fig. 1 (A) for oxygen transfer analysis, in which the three pp hollow fibers were considered as one. With the appropriate dimensionless variables the governing equations and the boundary conditions are given as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P_m}{\partial r}\right)=0, \qquad 1\leq r\leq r_o \tag{1}$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial P_l}{\partial r}\right)=\phi^2, \qquad r_p^s\leq r\leq 1 \tag{2}$$

$$\text{at } r=r_o, \qquad P_m=1 \tag{3}$$

$$r=r_l=1, \qquad P_m=P_l \tag{4}$$

$$\frac{\partial P_m}{\partial r}=\beta\frac{\partial P_l}{\partial r} \tag{5}$$

$$r=r_t, \qquad P_l=0 \tag{6}$$

$$\frac{\partial P_l}{\partial r}=0 \tag{7}$$

where

$$\phi=R_l\left(\frac{Q_{O_2}\cdot x}{S_l D_l P_o}\right)^{\frac{1}{2}}, \quad \beta=\frac{S_l D_l}{S_m D_m}$$

Other quantities are defined in the nomenclature section. The solutions to eqs. (1) through (5) and (7) are

$$P_m=1-\frac{1}{2}\beta\phi^2(1-r_t^2)\ln(r_o/r) \tag{8}$$

$$P_l=1+\frac{1}{4}\phi^2(r^2-1)-\frac{1}{2}\phi^2 r_t^2\ln(r)-\frac{1}{2}\beta\phi^2(1-r_t^2)\ln(r_o) \tag{9}$$

Using eqs. (6) and (9), dimensionless oxygen penetration depth ($1-r_t$) is obtained from

$$\frac{1}{2}r_t^2\ln(r_t)+\frac{1}{4}[1+2\beta\ln(r_o)](1-r_t^2)-1/\phi^2=0 \tag{10}$$

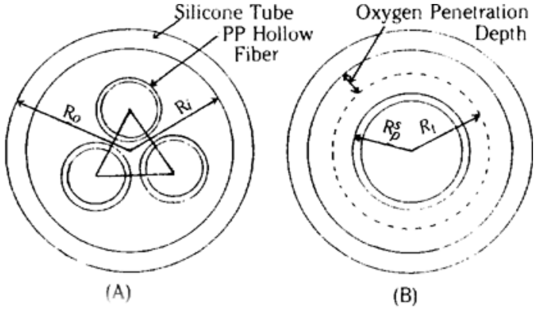

Fig. 1. Schematic of dual hollow fiber unit; (A) original, (B) simplified.

*To whom all correspondence should be addressed.

Table 1. Data used for oxygen transfer analysis [1].

s_l	= 3.8×10^{-4} (std $cm^3/cm^3/cmHg$)
s_m	= 4.1×10^{-3} (std $cm^3/cm^3/cmHg$)
D_l	= 0.8×10^{-5} (cm^2/s)
D_m	= 1.5×10^{-5} (cm^2/s)
β	= 0.05
P_o	= 76 cmHg (pure oxygen)
	= 15.96 cmHg (Air)
x	= 500 g/l (ref. 3)
Qo_2	= 0.38 ml/min/gDW (ref. 8, free *A. niger* pellets after 20 h culture)
Silicone tube (Dow Corning, USA):	
$R_o = 0.09779$ cm, $R_i = 0.07366$ cm	
Polypropylene hollow fiber (Enka, FRG):	
$R_p = 0.0315$ cm	

Oxygen uptake rate (OUR) is given by

$$\text{OUR} = S_m D_m \frac{\partial P'_m}{\partial R}\bigg|_{R=R_i} (2\pi R_i L) \qquad (11)$$

Using eqs. (8) and (11), volumetric oxygen uptake rate (VOUR) defined as OUR/Volume of immobilized cells becomes

$$\text{VOUR} = Q_{O_2} \cdot x \cdot (1 - r_t^2) \,/\, (1 - r_p^2) \qquad (12)$$

Using the data given in Table 1, partial pressure of oxygen, oxygen penetration depth, and VOUR were

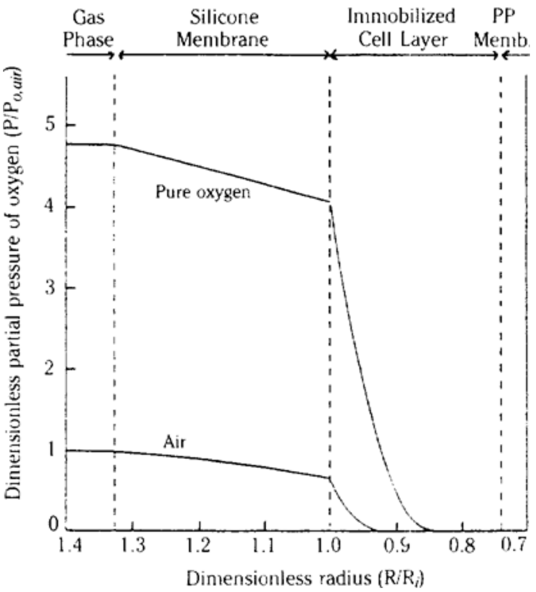

Fig. 2. Profiles of the dimensionless oxygen partial pressure in a dual hollow-fiber unit.

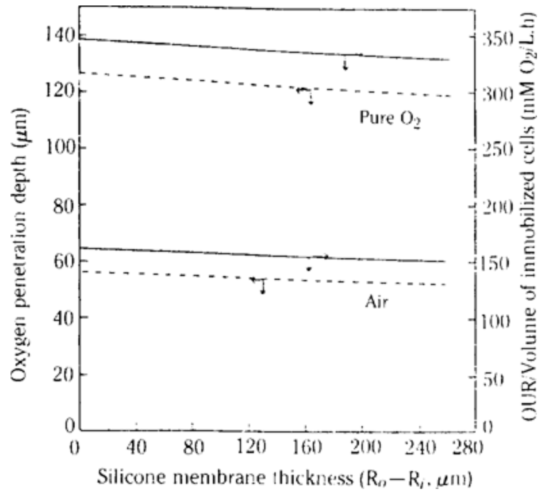

Fig. 3. Oxygen penetration depth and OUR/Volume of immobilized cells vs. silicone membrane thickness. Data of Table 1 except R_o were used.

calculated. Figure 2 shows profiles of the oxygen partial pressure in a dual hollow-fiber unit. As shown in this figure, major portion of oxygen transfer resistance exists in the immobilized cell layer. In Figure 3 oxygen penetration depth and VOUR according to the variation of the silicone membrane thickness are shown. Although the silicone membrane thickness increases from zero to 250 um, oxygen penetration depth and VOUR are almost constant. Oxygen penetration depth and VOUR in the case of pure oxygen are ca. 2.4 times those in the case of air. Silicone membranes have been used for oxygen enrichment due to high oxygen permeability compared with other polymeric materials. In this study the silicone membrane thickness did not appear to be a critical factor in the reactor design.

Conclusively, length of the immobilized cell layer rather than the silicone membrane thickness was a critical factor in the dual hollow-fiber bioreactor design.

NOMENCLATURE

- D : diffusivity of oxygen (cm^2/sec)
- L : length of the dual hollow-fiber (cm)
- P : dimensionless partial pressure of oxygen ($P = P'/P_o$)
- P′ : partial pressure of oxygen (atm)
- P_o : uniform partial pressure of oxygen outside silicone tube (atm)
- Q_{O2} : specific oxygen uptake rate (mmol O_2/g DW cell·h)

r : dimensionless radial coordinate ($r = R/R_l$)
R : radial coordinate (cm)
s : solubility of oxygen (mol/L·atm)
x : cell mass density (g DW/L)

Greek Letters

β : ratio of oxygen permeability in the silicone membrane to that in the cell layer ($\beta = s_l D_l / s_m D_m$)

ϕ : Thiele modulus $[\phi = R_l (\frac{Q_{O_2} \cdot x}{S_l D_l P_o})^{\frac{1}{2}}]$

Superscript

s : simplified model of a dual hollow fiber unit

Subscripts

i : inner silicone tube
m : silicone membrane
l : cell layer
o : outer silicone tube
p : pp hollow fiber

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