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Bioreactor Performance and Design of Large Scale Packed-Bed Solid-State Fermentation

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ABSTRACT

Bioreactor performance and design was investigated by simulating a transient two-dimensional heat transfer model. The model was able to describe the microbial growth and death kinetics and the energy balance in both axial and radial directions at any location in packed-bed solid-state fermentation. The emphasis of heat conduction, convection and the effect of evaporation made the model particularly useful and practical for large-scale investigation in which the overheating is critical. The system was simplified by assuming pseudo-homogeneous and constant values of bed physical and thermal properties. Orthogonal collocation technique was applied to solve the equations. The characteristic of temporal temperature and biomass concentration profiles in two dimensions were predicted.

The effects of various design and operating variables on the performance of the 10 m^3 were explored, with the aim of identifying strategies to minimize overheating at the top of the bed. Superficial velocity and inlet air temperature were found to have significant effects on the bioreactor performance. Superficial velocities of 0.08 to 0.1 m/s are required for effective convective heat removal. A low inlet air temperature (308 to 312 K) leads to overheating after 10-20 h which cause all organisms to die. The geometric ratios of 1.0 and below minimized overheating problems and lead to high growth rates.

Key words : large-scale bioreactor, bioreactor performance and design, solid-state fermentation

INTRODUCTION

Solid-state fermentation (SSF) involves the growth and metabolism of microorganisms on moist solid materials, in the absence or near absence of free water (Moo-Young *et al.*, 1983; Mitchell and Lonsane, 1992). This limited availability of water makes SSF fundamentally different from submerged liquid fermentation (SLF).

Solid-state fermentation is relatively rare in western countries, but has been practiced for thousands of years in Asia, in the production of fermented foods. However, these processes have been developed and optimized by trial and error over many generations, and therefore the fundamental processes occurring are not well understood. Some processes have been industrialized, such as the koji stage of soy sauce manufacture, however the technology that has been developed is largely proprietary.

The performance of SSF processes depends on interactions between the 3 main components of the system: the microorganism, the substrate and the bioreactor (Sangsurasak and Mitchell, 1995a;

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1995b). This study will investigate the process from the perspective of bioreactor performance and design.

SYSTEM

The bioreactor is a cylindrical bioreactor, packed with a bed of substrate particles of uniform size as shown in Figure 1. These substrate particles are assumed to have the properties of starch at 50% moisture content, such as might be expected if sago-beads are used as a substrate, as was done by Gumbira-Sa'id *et al.* (1991). The bed is treated as a pseudo-homogeneous matrix. Therefore the thermal and physical properties of the bed are calculated as a weighted sum of the properties of the substrate particles and the air in the bed. The thermal and physical properties of the pseudo-homogeneous bed were assumed to be independent of temperature, which is reasonable given the relative small range of less than 20°C which will be experienced in the bed.

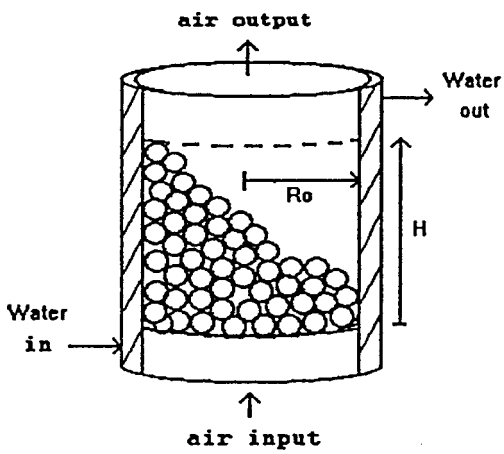


Figure 1 Packed bed bioreactor.

MATHEMATICAL MODEL

The mathematical model was developed to describe the system in Figure 1. The model consists of two parts; growth and death kinetics and the heat transfer phenomena. Biomass is divided into two types in this investigation, viable biomass or reproductive cells and dead biomass or non-reproductive cells. The sum of viable and dead biomass, therefore, becomes the total biomass. A common empirical kinetic model, the logistic equation, was used to describe microbial growth in this investigation.

The equations are transformed into dimensionless form and all the parameters are grouped and converted into dimensionless terms as follows.

$$Z = \frac{z}{H} \quad , \quad z = ZH$$

$$R = \frac{r}{R_o} \quad , \quad r = RR_o$$

$$\tau = \frac{v_z . t}{z} \quad , \quad t = \frac{z.\tau}{v_z} \qquad (1)$$

$$\theta = \left(\frac{T - Ti}{T_{surr} - T_i} \right) , \quad T = [\theta.(T_{surr} - T_i)] + T_i$$

$$Pe = \frac{\rho_b . C_{p,b} . v_z . d_p}{k_b}$$

where z is the bed height position
Z is dimensionless bed height
H is the bed height (as indicated in Figure 1)
r is the radial position
R is dimensionless bed radius
R_0 is the overall bed radius (as indicated in Figure 1)
τ is dimensionless time
θ is dimensionless temperature

T is the temperature
T_i is the initial temperature of the bed
T_{surr} is the temperature of the surroundings or coolant
Pe is the dimensionless Peclet number
d_p is the particle diameter
v_z is the superficial air velocity
$C_{p,b}$ is the bed heat capacity
k_b is the bed thermal conductivity
ρ_b is the bed density

Dimensionless equations

By substituting the dimensionless terms (equation 1) into the equations, a set of dimensionless equations were obtained. The heat transfer equation becomes:

$$\frac{\partial\theta}{\partial\tau} = -\left(\frac{\rho_{ma}.C_{p,ma} + C_{p,a}.f.\lambda}{\rho_b.C_{p,b}}\right)\frac{\partial\theta}{\partial Z} + \left(\frac{d_p.H}{Pe,R_0^2}\right)$$

$$\left(\frac{1}{R}\cdot\frac{\partial\theta}{\partial R} + \frac{\partial\theta}{\partial R^2}\right) + \left(\frac{d_p}{Pe.H}\right)\frac{\partial^2\theta}{\partial Z^2} + Q \qquad (2)$$

initial condition

$$\tau = 0, \quad \theta = 0 \qquad (3)$$

boundary conditions

$$R = 0, \quad \frac{\partial\theta}{\partial R} = 0 \qquad (4)$$

$$R = 1, \quad \frac{\partial\theta}{\partial R} = Bi(1-\theta_{surr})$$

$$Z = 0, \quad \theta = \theta a$$

$$Z = 1, \quad \frac{\partial\theta}{\partial Z} = 0$$

where Bi is the dimensionless Biot number
θ_{surr} is the dimensionless temperature of the surroundings or coolant
θ_a is the dimensionless temperature of air

The dimensionless heat generation term, Q, is a function of Pe number.

$$Q = \left(\frac{d_p.H}{Pe.k.(T_b - T_i)}\right).q \qquad \textbf{(5)}$$

Equation (6), (7) and (8) show the dimensionless total, viable and dead biomass production rate

$$\frac{dB_t}{d\tau} = \frac{H.\mu_g}{v_z}.B_v.(1-B_t) \qquad (6)$$

$$\frac{dB_v}{d\tau} = \frac{H}{v_z}\left[(\mu_g.(1-B_t) - \mu_d).B_v\right] \qquad (7)$$

$$\frac{dB_d}{d\tau} = \left(\frac{H.\mu_d}{v_z}\right).B_v \qquad (8)$$

where B_t is the dimensionless total biomass (X_t/X_m)
B_v is the dimensionless viable biomass (X_v/X_m)
B_d is the dimensionless dead biomass (X_d/X_m)

NUMERICAL METHOD

The equations are solved numerically by a mixture of orthogonal collocation method (Finlayson, 1980; Villadsen and Michelsen, 1978; Sangsurasak *et al.*, 1993) and the Backward Euler method (Hindmarsh, 1974). The model is verified by comparing with the experimental data of Saucedo-Castaneda *et al.* (1990) Sangsurasak, (1996), Sangsurasak *et al.*, (1997).

RESULTS AND DISCUSSION

The demonstration on how the model can give an insight into packed bed performance and the effect of size and operational and design parameters on the performance is developed. The system of interest is the growth of *Rhizopus oligsporus* on the starchy substrates. Simulations

were done for a large bioreactor size of 10 m^3 and the simulation time is 90 hours. This two-dimensional geometry enables temperature, and viable and dead biomass profiles to be predicted for any location inside the bed. However, only the collocation point in the upper region of the bed where the highest temperatures occur will be investigated and discussed in this paper.

Figure 2 demonstrates the effect of air velocity on temperature together with viable and dead biomass concentration. At an air velocity of 0.02 m/s the temperature increases significantly during the early stages of fermentation (Figure 2a), leading to the death of all organisms by 20 hours (Figure 2c). Superficial air velocities as high as 0.08 to 0.1 m/s are required to maximize the viable biomass density obtained (Figure 2b).

Figure 3 shows the effects of inlet air temperature on system temperature and cell concentrations. The inlet air temperature as low as 298 K leads to the lowest maximum bed temperature but this bed temperature is close to the optimum for growth (Figure 3a). Therefore, the growth rate is the highest (Figure 3b) and there is negligible death (Figure 3c). At lower regions of the column the temperature will be lower than at the upper region leading to a slower growth rate. With the inlet air temperature close to the optimum for growth (308-312 K), rapid growth occurs for a short period of 10-20 hours (Figure 3b), but the temperature quickly increases to values (Figure 3a) which cause all the organisms to die (Figure 3c).

Figure 4 indicates that the strategy of maintaining the superficial air velocity while decreasing the H/D ratio (height per diameter ratio) will give significantly better performance for packed bed bioreactor in SSF. At H/D ratios of 1.0 and below, the temperature profiles were less pronounced (Figure 4a) and good growth (Figure 4b) and negligible death (Figure 4c) were predicted.

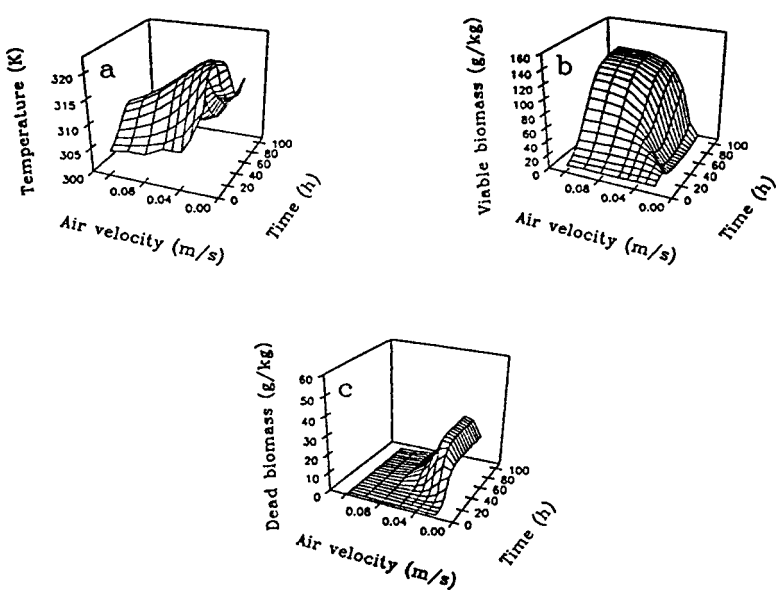


Figure 2 The dynamic effect of air velocity on the system temperature (a), viable biomass (b), and dead biomass (c).

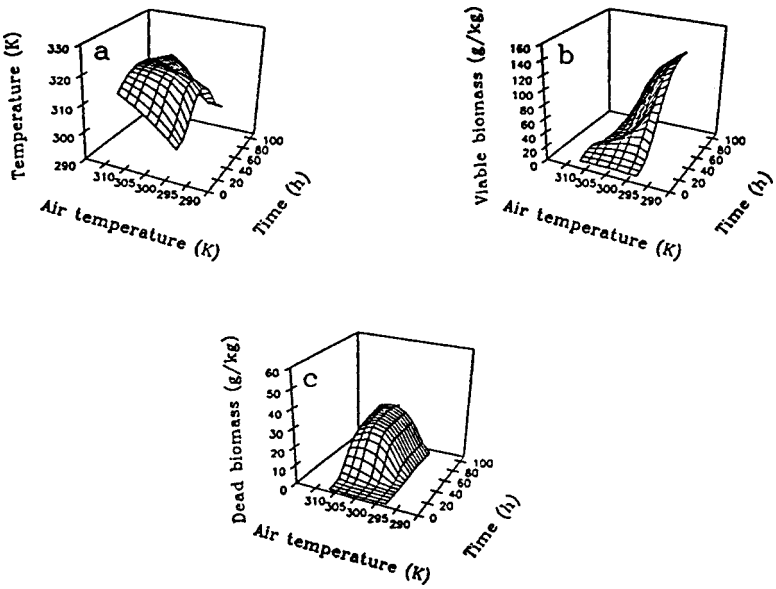


Figure 3 The dynamic effect of inlet air temperature on the system temperature (a), viable biomass (b), and dead biomass (c).

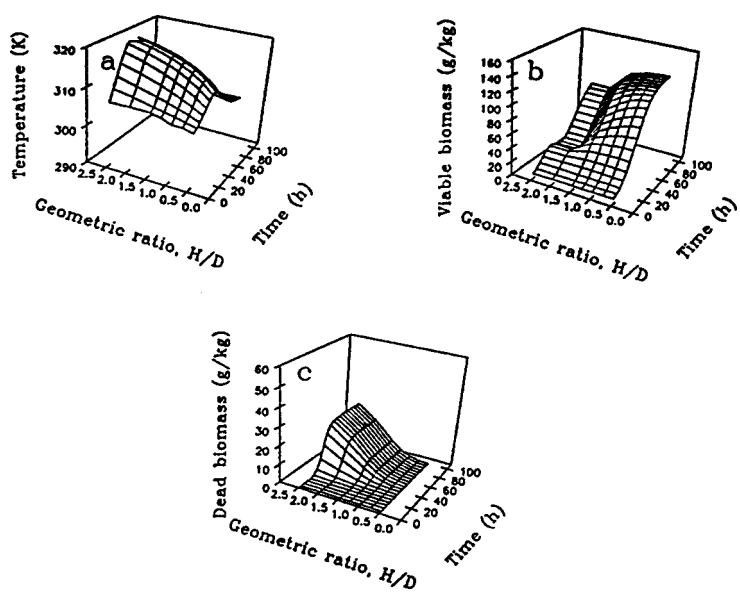


Figure 4 The dynamic effect of bioreactor geometric raio on the system temperature (a), viable biomass (b), and dead biomass (c).

CONCLUSION

The transient two-dimensional heat transfer model developed can be used as a tool aiding the design, operation and scale-up of packed bed which can be used to inform design decisions for larger scale packed bed bioreactors. Superficial air velocity, inlet air temperature and geometric ratio are predicted to have significant effects on the temperature and growth in the upper regions of the packed bed.

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