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The influence of heat and mass transfer on solid state fermentation

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Solid state fermentation is an effective cultivation method successfully used for enzyme production. Uniform and stable cultivation conditions in solid medium are essential for high production yield.

Heat generated during microbial growth is conducted in a solid bed and transferred to air. As a result a gradient of temperature in solid medium is created. The temperature gradient in the bed affects growth of microorganisms. When the temperature in the bed exceeds a critical value the yield of enzyme decreases. The effect of heat and mass transfer on solid state fermentation was discussed qualitatively only [1]. The mathematical models of solid state fermentation do not include the effect of temperature distribution in the solid medium [2, 3].

In the present work a simplified method for calculation of the temperature profile in solid material during solid state fermentation is discussed. The mathematical model makes possible a quantitative analysis of the influence of various parameters, such as air flow rate, air temperature and humidity, and bed width, on the solid state fermentation.

The mathematical model of solid state fermentation consists of a description of microbial growth kinetics, heat generation rate, heat conduction in the solid substrate, and heat and mass transfer on the solid-air surface.

In the present analysis a layer of solid substrate resting on a metal tray of negligible thermal resistance with humid air flowing over the material and also below the tray is considered (Fig. 1).

The kinetics of microbial growth is described by a logistic curve [2, 3]:

$$\frac{dX}{d\tau} = k_X X \left(1 - \frac{X}{X_m}\right) \tag{1}$$

As is known, the kinetic constant k_X depends on temperature.

The heat generation rate is expressed in growth and maintenance terms as follows:

$$q_v = \rho\frac{dQ}{d\tau} = \rho Y_{QX} \left(\frac{dX}{d\tau} + mX\right) \tag{2}$$

The heat conduction in the solid material is described by equation:

$$\rho c_p \frac{\partial T}{\partial \tau} = \lambda \nabla^2 T + q_v \tag{3}$$

The initial condition is:

$$\tau = 0 \quad T(0, z, y) = T_0 \tag{4}$$

The boundary conditions for equation (3) are:

$$\begin{aligned} z &= 0 \quad -\lambda \frac{\partial T}{\partial z} = \alpha_b \left(T(\tau, y, 0) - t_p\right) \\ z &= \delta \quad T(0, y, \delta) = T_S \end{aligned} \tag{5}$$

The first equation describes the heat transfer from the tray. The second refers to the temperature on the solid-air surface. This temperature may be calculated from heat balance at the surface:

$$-\lambda \left(\frac{\partial T}{\partial z}\right)_{z=\delta} = \alpha (T_S - t_p) + k_Y r (Y_S - Y_p) \tag{6}$$

Heat and mass transfer coefficients are related to each other by:

$$\frac{\alpha}{k_Y} = C_H \tag{7}$$

where C_H is specific heat of humid air.

Figure 2 shows the dependence of T_S, surface temperature on the heat transfer coefficient α. For high values of this coefficient the surface temperature is almost independent of the heat generation rate.

One can solve this model numerically. In this work some simplification of the model will be

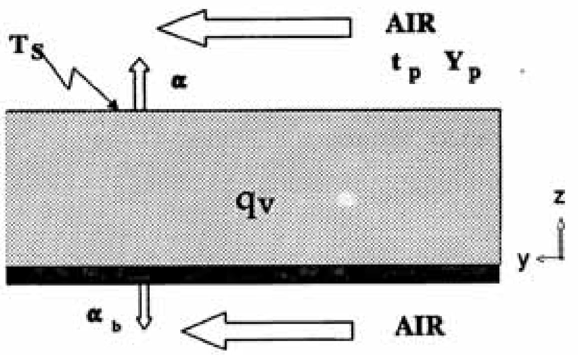

Fig. 1. Schematic diagram of solid state fermentation

presented. As the microbial growth is much slower than transport phenomena a quasi-steady state may be assumed. The temperature gradient along the bed is neglected. The influence of temperature on the heat generation rate is also neglected. For such a simplified model the temperature profile in the bed is:

$$T = -\xi^2\Theta + \frac{N_{Bi}}{N_{Bi}+1}(T_S - t_p + \Theta)\xi + \frac{T_S + \Theta + N_{Bi}t_p}{N_{Bi}+1} \qquad (8)$$

where:

$$\Theta = \frac{q_v\delta^2}{2\lambda}$$
$$N_{Bi} = \frac{\alpha\delta}{\lambda}$$
$$\xi = \frac{z}{\delta} \qquad (9)$$

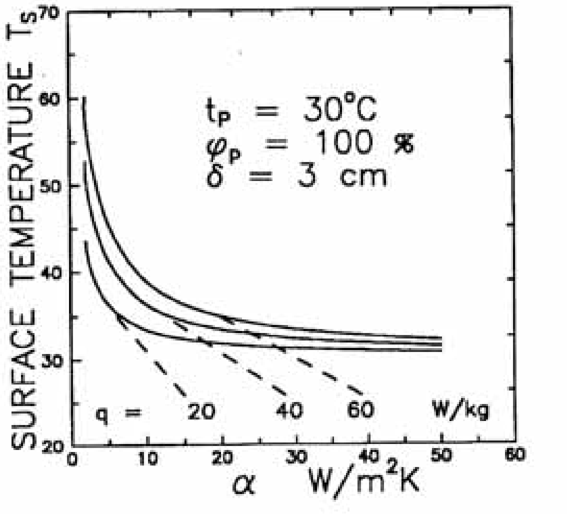

Fig. 2. The dependence of the surface temperature on the heat transfer coefficient

Θ is the temperature difference between the bottom of the solid medium and its surface in the case when heat is not exchanged from the tray. The increase of heat flux from the tray to air decreases the temperature differences in the bed, thus Θ gives the maximum possible temperature difference in the bed.

Figure 3 shows temperature profiles in the bed for two values of the heat transfer coefficient. The profiles when no heat is exchanged from the tray are also presented. The results show that heat exchange from the tray is important for stabilization of the temperature and can not be omitted in the model.

In our experimental study on cultivation of *Aspergillus niger* on wheat bran, values of kinetics parameters were estimated [4]. In the present calculation some average values were used: $k_X = 0.2\ h^{-1}$, $X_0 = 0.001 \times X_m$, $Y_{QX}X_m = 4$ kJ/g. Using these values the temperature of the surface and the maximum temperature in the solid medium were calculated. Figure 4 presents the results of these calculations. For a high value of the heat transfer coefficient the surface temperature is almost constant during cultivation. The maximum of the bed temperature reaches the highest values at the time when microbial growth rate is the highest.

The results of calculation point to the important role which transport phenomena play in solid state fermentation. The high heat transfer rate is necessary to avoid a high temperature gradient in the solid medium. The heat transfer from the tray contributes significantly to the

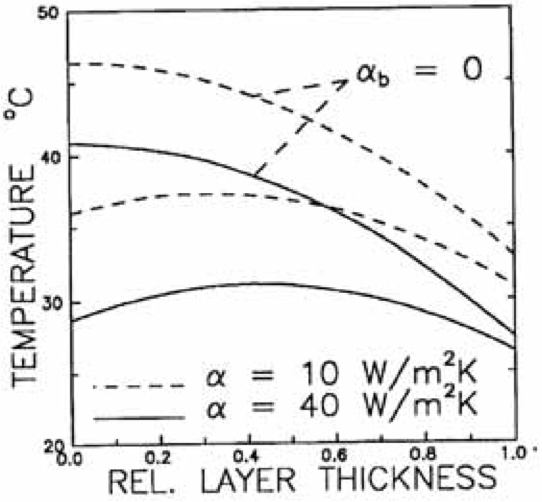

Fig. 3. The influence of the heat transfer on temperature profile in the solid medium

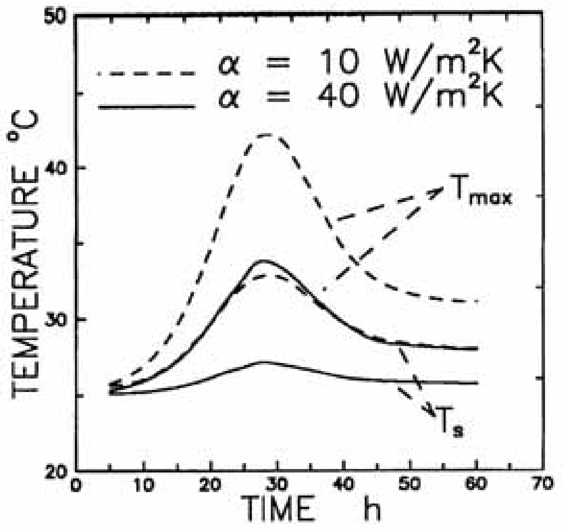

Fig. 4. Time course of the surface temperature and the maximum temperature in the solid medium during cultivation

overall heat transport. A sufficient heat transfer may be obtained for high air flow rates and a special construction of fermentor.

SYMBOLS

C_H, specific heat of humid air; C_P, specific heat of solid medium; k_X, kinetic constant; k_Y, mass transfer coefficient; m, maintenance coefficient; q, heat generation rate; q_v, volumetric heat generation rate; r, specific evaporation heat; T, temperature of solid medium; T_{max}, maximum of the bed temperature; T_0, initial temperature of solid medium; T_S, surface temperature; t_p, air temperature; Y_P, air humidity; Y_S, humidity of saturated air at temperature T_S; Y_{QX}, proportionality coefficient; X, biomass; X_o, inoculum mass; X_m, parameter in kinetic equation; y, coordinate; z, coordinate; α, heat transfer coefficient; α_b, heat transfer coefficient for tray; δ, solid layer width; φ_p, relative humidity of air; λ, heat conductivity; ρ, density of solid medium; τ time.

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