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REVIEW ARTICLE

Fluidized Bed Reactor as Solid State Fermenter

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ABSTRACT

Various reactors such as tray, packed bed, rotating drum can be used for solid-state fermentation. In this paper the possibility of fluidized bed reactor as solid-state fermenter is considered. The design parameters, which affect the performances are identified and discussed. This information, in general can be used in the design and the development of an efficient fluidized bed solid-state fermenter. However, the objective here is to develop fluidized bed solid-state fermenter for palm kernel cake conversion into enriched animal and poultry feed.

Keywords: solid-state fermentation, fluidized bed reactor, palm kernel cake, poultry feed

INTRODUCTION

Solid-state fermentation is defined as the growth of microorganisms on moist solid substrates without free flowing water. This technique, even though very ancient attracted attention recently to develop commercially viable processes such as production of ethanol from cassava roots and sugar beets, enzymes, organic acids, biogas, antibiotics, mushrooms, surfactants, biocides etc. (Raghavarao *et al*, 2003).

Various parameters that affect the production of bio-products are particle characteristics of the substrate, uniform distribution of inoculums over the substrate, the contact between the substrate and the microbes, efficient removal of metabolic heat from the substrate, diffusion of O_2 through the substrate, removal of byproduct gases as and when they form, maintenance of desired moisture in the substrate etc. Control of most of these parameters depends on the type of reactor chosen for fermentation. For example, in packed bed solid-state fermenter, poor heat removal and non-uniform growth of microorganism are observed (Doelle *et al*, 1992). In other reactors such as rotating drum, perforated drum and tray reactor, the mixing is less efficient. In these reactors, due to poor mixing, agglomeration of substrate particles during the growth of mycelium can occur increasing the difficulty of regulating the temperature of the substrate. Further, the diffusion of oxygen to these agglomerates will be very low or sometimes nil. Metabolic heat removal through the walls of the reactor is very difficult if the body of the reactor moves as in rotating drum. If there is no proper movement of the substrate solid particles inside the reactor, the maintenance of proper moisture content is difficult. Most of these problems can be efficiently handled in a fluidized bed reactor in which the particles move independently like a fluid and the heat and mass transfer coefficients are very high between particle to gas, gas to particle, or bed to surface and surface to bed (Kunii and Levenspiel, 1999).

Specific advantages when fluidized bed is used as a fermenter to conduct solid-state fermentation reactions are

1. Efficient removal of metabolic heat by the gas phase fluidizing medium
2. Healthy and good growth of aerobic microorganisms due to very good aeration by the fluidizing air
3. Quick scavenging of gaseous and volatile metabolic products which inhibit the fermentation process
4. *In situ* drying of the product if required
5. Absence of temperature and moisture gradients due to good mixing of solid substrate which also enables superior control of process parameters
6. Small substrate particles provide lot of surface area for better transfer of heat and mass, and microbial growth.
7. Higher productivities compared to traditional solid-state fermentation process resulting in savings of plant space and operating costs.

Since fluidized be reactor, as solid-state fermenter seems to be one of the most efficient systems, this paper attempts to discuss the preliminary design considerations and the parameters. The ultimate aim of this work is to design and operate a fluidized bed solid-state fermenter to convert palm kernel cake (PKC) as animal or poultry feed.

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DESIGN PARAMETERS

The design of any reactor requires information on the hydrodynamics, transport processes, kinetics and contacting of the system involved. The parameters related to hydrodynamics, transport processes and chemical reaction are discussed in the following paragraphs.

Fluidization is the technique in which fine solids are kept in suspension by the up flow of fluid. The fluid can be either gas or liquid. In solid-state fermentation, the upward flowing fluid is air. A typical fluidized bed reactor is shown in Figure 1.

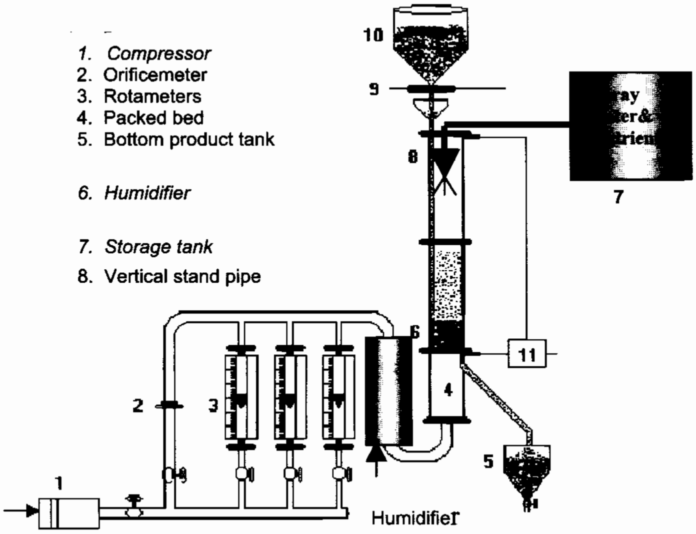

Figure 1: Typical schematic of a fluidized bed fermenter

The following are the design and operating parameters to be considered in the analysis, design and operation of fluidized bed solid-state fermenter:

1. Particle size
2. Minimum fluidization velocity
3. Pressure drop across the bed
4. Pressure drop due to distributor plate
5. Bed height
6. Terminal velocity of particles
7. Heat and mass transfer characteristics
8. Moisture distribution in the bed
9. Reactor models based on contacting pattern

The design parameters mentioned above are briefly discussed below:

1) Particle size

The type of fluidization particularly in gas-solid systems is related to the properties of solids and the fluidizing gas medium. Geldart (1973) classified the powders into four groups as shown in Figure 2.

The groups were designated as A, B, C and D. These groups are characterized by the difference in density between the particle and the fluidizing gas, and the mean size of the particle. Of these four groups, the two extreme groups are Group C, which is difficult to fluidize and Group D, which is spoutable. The intermediate Groups A and B are suitable for the fluidization operation. Of these two groups, Group A powders have dense phase expansion after minimum fluidization but prior to the commencement of bubbling, where as Group B powders exhibit bubbling at the minimum fluidization velocity itself. Group A powders are often referred to as “aeratable powders” and Group B powders as sand like powders. Geldart classification has been modified by Molerus (1982) and Grace (1986). However the basic features of types of fluidization can be interpreted using the following simple criteria adopted by Geldart (1973):

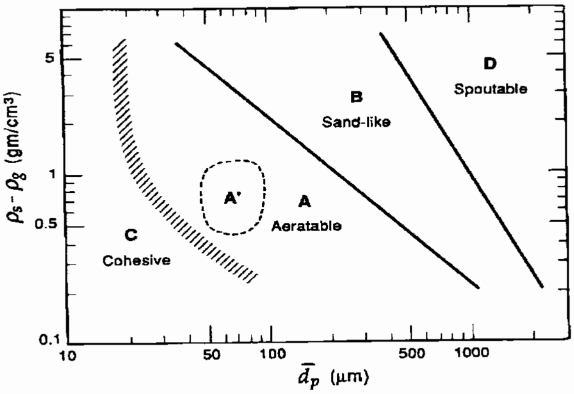

Figure 2: Geldart’s classification of solids for fluidization

for Group A $\left(\rho_S - \rho_f\right) d_p \leq 225$ ..... (1)

for Group D $\left(\rho_S - \rho_f\right) d_p^2 \geq 10^6$ ..... (2)

Equation (1) is the boundary between Group A and Group B powders where as equation (2) is the boundary between Group B and Group D. Geldart classification gives a priori an idea of the type of fluidization to be expected, once the physical properties of the particles and fluidizing medium are known.

2) Minimum fluidization velocity

At the point of minimum fluidization velocity the drag force exerted by the fluidizing medium on the particles is balanced. Using this criterion Wen and Yu (1966) developed an equation for calculating the minimum fluidization velocity as

$$\mathrm{Re}_{mf} = \left[33.7 + 0.0408 Ar\right]^{1/2} - 33.7 \qquad ..... (3)$$

where $\mathrm{Re}_{mf} = \dfrac{d_p u \rho_f}{\mu}$

$$Ar = \frac{g d_p^3 \rho_f \left(\rho_s - \rho_f\right)}{\mu^2}$$

Even though many correlations are available to predict minimum fluidization velocity, Equation (3), is still widely used in the literature. Equation (3) predicts the minimum fluidization velocity with an error of around ± 40%. Hence, it is normally recommended to measure the minimum fluidization velocity experimentally using the same particles that to be fluidized.

3) Pressure drop across bed

Pressure drop across the bed can be estimated using the force balance at the point of minimum fluidization velocity from the equation,

$$\Delta P = \left(1 - \varepsilon_{mf}\right)\left(\rho_s - \rho_f\right) g \qquad \text{..... (4)}$$

4) Pressure drop due to distribution plate

One of the essential components in the design for better distribution of fluidizing medium to facilitate uniform fluidization is the distributor / perforated plate. The pressure drop across this plate is normally used as 20-40% of the pressure drop across the bed.

$$\Delta P_d = \left(0.2 - 0.4\right) \Delta P \qquad \text{..... (5)}$$

However, in industrial columns, the pressure drop across the distributor should be as minimum as possible with out sacrificing the equality of fluidization. Equations (4) and (5) give the total pressure drop that has to be overcome by the fluidizing medium, which determines the capacity of the compressor or blower.

5) Bed height

For better fluidization, generally it is recommended that the ratio of bed height to diameter of the tube as

$$\frac{H}{D} = 1 - 2 \qquad \text{..... (6)}$$

If this ratio is more than 5, slugging is encountered in the bed, resulting poor contact between the fluidizing medium and the solids. For most of the laboratory studies equation (6) can be used. The industrial reactors may operate at higher ratios sacrificing the quality of fluidization.

6) Terminal velocity of the particles

If the velocity of the individual particle exceeds the terminal velocity, the particles are blown out of the bed. This velocity is one of the boundaries for maintaining fluidization. In other words the fluidization regime is between minimum fluidization velocity and the terminal velocity of the particles. Haider and Levenspiel (1989) give an equation for terminal velocity of spherical particles as

$$u_t = \left[\frac{4 d_p \left(\rho_s - \rho_f\right) g}{3 \rho_f C_D}\right]^{1/2} \qquad \text{.......... (7)}$$

where

$$C_D = \frac{24}{\mathrm{Re}_p}\left[1 + \left(8.1716 e^{-4.0655\varphi_s}\right) \mathrm{Re}_p^{\,0.0964+0.5565\varphi_s}\right] + \frac{73.69\, \mathrm{Re}_p\, e^{-5.0748\varphi_s}}{\mathrm{Re}_p + 5.378 e^{6.2122\varphi_s}} \qquad \text{...... (8)}$$

For spherical particles

$$C_D = \frac{24}{\mathrm{Re}_p} + 3.3643\, \mathrm{Re}_p^{0.3471} + \frac{0.4607\, \mathrm{Re}_p}{\mathrm{Re}_p + 2682.5} \qquad \text{... (9)}$$

7) Heat and Mass transfer characteristics

In solid-state fermentation, the heat must be transferred from the solid substrate, where it is generated due to the metabolic activity of the microorganisms and is to be removed by the fluidizing medium. This mode of heat transfer in a fluidized bed is termed as particle to fluid heat transfer. For calculating the heat transfer coefficient, Ranz and Marshall (1952) correlation to single particle, has been modified for multi-particle system.

For $\mathrm{Re}_p > 100$ $\quad Nu_p = 2 + 1.8\, \mathrm{Re}_p^{1/2}\, \mathrm{Pr}^{1/3}$ .....(10)

For $\mathrm{Re}_p < 100$, the contribution of the convective component is negligible and $\mathrm{Nu}_p = 2$, when Re_p tends to zero. If the metabolic heat is not controlled by the fluidizing medium, heat can also be removed by providing an external jacket around the bed or by immersing a cooling surface inside the bed. However it should be noted here that the heat transfer mechanism in fluidized beds is highly complex and involved.

The mass transfer steps in a fluidized bed can generally be classified as transfer between particle and the fluidizing medium, and transfer between lean (bubble) and dense (emulsion) phases.

Wakao (1984) proposed a correlation for predicting the particle-fluid mass transfer over a large range

For $3 < \mathrm{Re}_p < 3000$ $\quad Sh = 2 + 1.1\, \mathrm{Re}_p^{0.6}\, Sc^{1/3}$ .... (11)

The mass transfer steps involved in solid-state fermentation using fluidized bed are (a) moisture transfer from humidified fluidizing medium to substrate, (b) O_2 transfer from fluidizing medium to the microbes which are on the outer and inner surface of the substrate particle, and (c) scavenging by-product gases from substrate to the fluidizing medium. Equation (11) can be used to estimate various mass transfer rates in fluidized bed solid-state fermenter (FBSSF).

8) Moisture distribution in the bed

One of the most important parameters in SSF is proper control of moisture to maintain the conditions for the growth of the microorganisms in the bed. In a FBSSF, this can be achieved by humidifying the fluidizing medium or by spraying required quantities of water from the top of the bed, which will get adsorbed on the solid surface. Fluidized bed is considered to be one of the best adsorbers and widely used in chemical industry. Further, the nutrients can also be uniformly distributed throughout the particles by spraying over the bed in liquid form.

9) Reactor models based on contacting pattern

To predict the conversion of the substrate in FBSSF, mathematical models to describe the reactor are to be used. Since FBSSF is a two phase reactor containing solid phase with micro-organism and fluidizing medium containing oxygen, proper contact must be maintained between these two phases. The substrate particle with microbe can be considered to be in perfectly mixed flow and the gaseous fluidizing medium in plug flow or in the form of bubbles depending on the velocity. The performance of the reactor can be expressed in terms of an equation as

$$Output = f\,[input,\ kinetics,\ contacting] \qquad \ldots\ldots (12)$$

Various types of reactor models, simple to complicated, have been proposed for fluidized beds such as mixed flow of solids and plug flow of gas, mixed flow of gas and solids, dispersed plug flow of gas and mixed flow of solids and, two phase models and bubbling bed models taking into account the presence of bubbles in the bed. A proper model has to be identified to describe the solid-state fermentation reaction in fluidized beds.

10) Applications of fluidized bed in solid state fermentation

The desirable conditions for SSF such as efficient removal of metabolic heat from the substrate, inter- and intra-phase oxygen diffusion into the substrate particle, and uniform distribution of inoculum as well as moisture can be easily handled in fluidized bed. Hence, fluidized bed reactors have tremendous potential in solid state fermentation of various substrates into valuable products.

Some applications of fluidized bed as solid state fermentor have been reported in the literature (Doelle *et al.* 1992, Bellon-Maurel *et al.* 2003). Moebus and Teuber (1982, 1985) reported the production of ethanol using fluidized bed. They studied anaerobic fermentation with CO_2 fluidizing medium for the continuous production of ethanol from glucose and starch using yeast. They also reported the synthesis of glutathione in a fluidized bed using ethanol producing yeast as ATP-regeneration and enzyme system.

Cell biomass and ethyl alcohol were produced in a fluidized bed reactor using 3.1 g of yeast and approximately 30% solids (Mishra *et al.* 1982). Tanaka *et al* (1986) reported the production of enzymes, amylase and protease using yeast in an air solid fluidized bed fermentor. Baker's yeast was produced in an air fluidized bed fermentor using potato substrate (Hong et al. 1987). Gas solid fluidized bed fermentor proved to be suitable for producing fungal starter culture (Tengerdy et al. 1987). Spores of *Chaetomium cellulolytium* and *Trichoderma reesei* were germinated on moist 30% furfural bran particles in a fluidized bed fermentor and used for fermentation of wheat straw. The starter culture containing about 12 mg/g (wet wt.) fungal biomas developed in 24 hours and was used without further processing for 9 months without losing viability.

All the above applications show the potential use of fluidized bed as solid state fermentor to produce products such as alcohols, enzymes, single cell protein, biomass etc.

CONCLUSIONS

In this paper an attempt is made to identify all the design parameters to consider fluidized bed as solid-state fermentor in which the favourable conditions such as efficient heat removal, good aeration, uniform distribution of moisture and inoculum etc can be met. The above parameters discussed, can be used to design a solid-state fermentor to convert palm kernel cake (PKC) to protein enriched animal and poultry feed.

NOMENCLATURE

Ar	*Archemedies number,*
D	*diameter of the column, m*
d_p	*diameter of the particle, m*
g	*acceleration due to gravity, m/s^2*
H	*Height of fluidized bed, m*
Nu_p	*particle Nusselt number,*
Pr	*Prandtl number,*
ΔP	*Pressure drop across the bed, Pa*
ΔP_d	*Pressure drop across the distributor, Pa*
Re_p	*Particle Reynold's number,*
Re_{mf}	*particle Reynold's number at minimum fluidization velocity,*
Sh	Sherwood number,
Sc	*Schmidt number,*
u_t	*Terminal velocity of the particle, m/s*
ε_{mf}	*porosity at minimum fluidization,*
μ	*viscosity of fluidizing medium, kg/m.s*

ρ *density of particle, kg/m^3*
ρ_f *density of fluidizing medium, kg/m^3*
ϕ_s *sphericity*

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