Chapter 2

Literature review of SSF design (Packed bed)
CHAPTER – 2

LITERATURE REVIEW OF SSF DESIGN
(PACKED BED)

The Chapter 1 deliberates the need of more research in SSF and hence in the same tune the objectives were set for the research work. The Chapter 2 states the literature review of SSF design and highlights the merits and demerits of each design, challenges of SSF applicability and range of fermented products produced by SSF using various cultures.

2.1 Introduction to SSF design

SSF is a multiphase system consisting of the solid phase, the thin liquid film, and the continuous gas phase. The different phases create many problems associated with mass and heat transfers, which are not still understood fully. SSF is a cost effective and environment friendly process. Hence, SSF is a thrust area for the technologists and scientists. However, precise control of the process variable is difficult in SSF and warrants a thorough literature survey. In view of new product development researchers have articulated newer SSF designs to impart better efficiency. However, still the majority of work has been stagnated to lab-scale and its transformation to pilot scale and large scale is still awaited. Although, some work has been done on this level; more works is the need of the time. SSF is an ancient technique to be transformed and modified for new tasks, using collective approaches of microbiology, biochemistry, biochemical engineering as well as advancement in instrumentation. Food fermentation and enzyme production are the main areas where SSF technology has immense application. Scientific research was concentrated on SSF after 1940’s in
view of developing and improving the production of drug penicillin. Penicillin was
developed using SmF as well as by SSF, however; with the advent of ease in
operation and precise control over the process SmF became the method of choice.
After 1970’s SSF technology was used for the production of protein enriched cattle
feed and for the production of enzymes \[1\]. C.W. Hesseltine was the one, who first
time published the scientific information on SSF in 1977. Kumar in 1987\[2\] has
reported medium scale production of enzymes, especially pectinases, in a scientific
manner for the first time in India. SSF has proved to be an attractive technique to
produce cellulase economically because of its lower capital investment and operating
cost \[3\]. The ease in operations and cost effective production of metabolites can act as
a magnet that can pull the investors and people from agroindustries to use SSF;
however it needs concerted efforts upon its interdisciplinary approaches. In order to
take full advantage of SSF potential, it is desirable to obtain a deep understanding of
the fermentation process.

2.2 Pros and cons of SSF

One of the most important and critical aspects of any commercially viable
fermentation technology is scaling up. Scaling up is more difficult in SSF, since, there
is no free flowing water present in SSF which creates difficulties for removing
metabolic heat. In SSF these heat can be removed by agitation or by forced aeration
while agitation brings undesirable effects leading to disruption of fungal mycelia. The
scale – up methods for SmF are well developed, these SmF scale-up methods could
not be applied directly to SSF \[4-5\] due to variation in physical structure of the systems
and inherent difference of availability of free flowing water. Hence, no assertive and
quantitative scale-up criteria are currently available for SSF. Cannel and Moo-
Young\textsuperscript{12} found that moisture variation poses a great difficulty in SSF design which is quite different from SmF. In order to address such problems many researchers have developed new models to address heat and mass transfer processes in packed bed solid state fermenter (PBSSF) \textsuperscript{[6,7]}, tray bioreactors\textsuperscript{[8,9]} and rocking drum bioreactors\textsuperscript{[10]}, which are commonly used in SSF. These models can be used to guide scale up processes in SSF\textsuperscript{[11]}. During the microbial growth, heat is generated by the metabolic activities of microorganisms. The heat generated during the process must be dissipated quickly since; microbial growth is very sensitive to a rise in temperature, affecting vegetative growth of fungal cells and that leads to formation of spores adversely affecting the product formation.

\textbf{2.3 SSF process methodology:}

Pretreatment of the lignocellulosic materials is very essential. Lignocellulose is a complex polymeric material containing cellulose, hemicelluloses and lignin. The pretreatment of such substrate involves generally heat treatment and chopping or cutting to a uniform size. The absence of pretreatment leads to poor growth and subsequently low product yield. Pore size of the substrate increases due to pretreatment and reduce the crystallinity of cellulose. The SSF process involves the following basic steps as shown in Fig. 2.1.
Fig. 2.1 SSF process flow chart
The design of SSFr is the key issue on which the success of the process relies. This design should be such that it shall maintain the optimum conditions favorable for microbial growth and product formation inside the reactor. Hence, common design of packed bed SSFr is discussed in the next subsection.

2.4 Common theoretical designs of packed bed

The objective of the fermenter design is to ensure that the desired activity of the micro-organisms shall not be limited by the characteristics of the equipment\textsuperscript{[34]}. The most significant aspect to be considered during the construction of a packed column of SSF is the effective distribution of air and heat removal. The effects of various designs and operating parameters on the performance of the PBSSF are discussed in Chapter 3 and 4. Heat transfer, channeling, flooding concepts have been theoretically discussed in this chapter.

2.4.1 PBSSF

For competent use of the process, larger fermentation volumes are needed. For large capacity, most commonly used vessel is the packed bed. PBSSF is a preferred design over most of the other designs because of better control and process management. The major design and operating parameters of the PBSSF include the height of the column and main parameters to be controlled are moisture of the bed and the temperature of the inlet air. PBSSF is a cylindrical vessel with perforated base and hemispherical head as shown in Fig.2.2. This vessel is filled with biomass as substrate where biomass itself is the source energy for micro-organism. The moisture to be maintained inside the column is 40% to 60%. PBSSF is cooled with water jacket from outside. Evaporation induced by forced aeration is a frequently used cooling method in large
scale PBSSF. Such evaporation is beneficial for SSF since it helps for cooling, but on the other side it is limiting the microbial growth by decreasing the moisture content from the bed. For large scale operation, the effectiveness of the water jacket reduces due to the decrease in the surface area for heat transfer to the volume of the substrate bed [26]. PBSSF is suitable for aerobic micro-organism. For aerobic fermentation generally air is forced from the bottom of column. PBSSF can be aerated from any point and for a vertical column the air may enter from either bottom or top. PBSSF is very easy for fabrication compared to another SSFr, but process parameters are very difficult to control. Perforated plate is situated at the bottom of the packed bed so that air can force through it. This kind of reactor can be used in two ways [6, 35]

i) To evaluate the overall process empirically and determine the process parameters

ii) To study O₂ diffusion along with mass and heat transfer phenomena

![Fig.2.2 Schematic representation of PBSSF](image)

**Fig.2.2 Schematic representation of PBSSF**
Heat accumulation is the major technical problem in almost all SSFr while it is more prevalent with large capacity of PBSSF. Microbial growth in SSF generates significant amount of metabolic heat. It has been reported that 100-300 KJ of heat per kg of cell mass is generated in a SSF process [36]. Several reasons are responsible for heat accumulation in PBSSF that include low thermal conductivity of substrate, absence of free water, channeling etc. High temperatures must be avoided inside a column, as they adversely affect on microbial activity. With the increase in bed height of the column the PBSSF temperature gradient gradually increases. When the temperature crosses the critical value, the growth of microbes is adversely affected. Hence, critical temperature is the main design parameter which determines the bed height of the fermenter. Heat generated inside a column is directly proportional to the metabolic activities of the micro-organism. For laboratory scale packed bed column, temperature can be controlled by wall cooling, however; in large scale packed bed column, conductive heat transfer is insufficient and hence convective mode of heat transfer needs to be used. Convective heat transfer is taking place due to evaporative cooling. Due to the absence of free flowing water and the poor conductivity of the substrate material, removal of heat is troublesome which finally generates temperature gradients inside the column.

Evaporation taking place inside a column also reduces water content of the bed. Minimum moisture level to be maintained in SSF is approximately 12% since all biological activities are ceased below this level [14]. In a static packed bed, the relative humidity of the inlet air is not a more useful controlling parameter because it is impossible to circulate humidified air equally through the packed bed. Hence water activity values vary within the bed. Evaporative water loss promotes bed drying and
need to be minimized in packed column. Gowthaman et al., (1993) [28-29] and Ghildyal et al., (1994) [27] showed that the rate at which bed drying occurs is dependent on the location within the bioreactor and the air flow rate. Water evaporation promotes the bed shrinkage in the column, although; bed shrinkage is a function of growth of hyphae on the surface of the substrate in majority. Spraying of humidified air does not stop the evaporation from the bed but can reduce evaporation loses from the bed compared to the dehumidified air. Heat transfer within the bed due to conduction is negligible. Majority of heat is transferred due to convection and evaporation [32,13].

Generally, bed temperature increases with increasing height of the bed [31]. The extreme temperature always posses greater problems than the oxygen availability to the microorganisms within PBSSF [33].

Metabolic heat is generated inside the packed column due to the action of microbes on substrate towards energy generation by respiration process. This is transferred to surrounding by two means (i) forced aeration and (ii) water jacket cooling. If packed bed column is divided vertically into various parts (A,B,C) as shown in Fig. 2.3 then it can be observed that part A is in vicinity of water jacket, where temperature gradient effect is less. As the substrate is bad conductor of heat water jacket effect in part B and C could be very minor. Hence, forced aeration plays an important role in part B and C. Again it can be said that part C may show high temperature gradient effect compared to part A and B.
If packed column is divided horizontally as shown in Fig. 2.4 then it can be observed that part C may face the problem of flooding (high moisture content) while part A and B of the bed may face the problems of dryness. In addition, temperature rise is more in part C followed by part B and A.
Channeling basically promotes the heat accumulation in a PBSSF. Channeling occurs when the gas is flowing through the packed bed and finds a “chosen/ideal or fixed path” through the bed (Fig. 2.5).

Bed shrinkage occurs due to three reasons, viz. (i) evaporation (ii) fungal growth and (iii) substrate consumption. Most of the biomass material gets shrink due to evaporation of water and fungal growth, this shrinkage again increase channeling problem in packed column. In large capacity column, it is hard to check practically whether channeling problem increases or not. Intensity of channeling problem can be decided from the moisture content of the upper layer of the bed. PBSSF tends to be very simple in design and even easy for loading and unloading but always critical to maintain desirable parameters. Forced aeration can be used in PBSSF for heat and mass transfer. But, it results in high temperature near the air outlet hence cooling system must be designed according to actual temperature gradient formed inside the PBSSF. High pressure drop is generated in a large capacity PBSSF which increase the
operating costs of the process. Generated pressure drop in PBSSF is mainly depends on three components viz. (i) height of the column (ii) substrate size and the way of packing components inside the column and (iii) the growth of micro-organisms. However, it further needs in-depth understanding the pressure gradient effect that has been discussed below.

2.4.2 Pressure gradients in PBSSF

In static operation, hyphae that grow into the inter particle spaces increase the pressure drop. Hypha tend to bind the substrate particles and form large agglomerates (Fig.2.6). The increase in pressure drop during the fermentation depends on the growth of microorganisms within the bed while, the pressure drop is also a function of the superficial velocity and the height of the PBSSF. Pressure drop parameter of the column is directly affecting the operating cost of the process especially the cost of generation of pressurized air through blower or compressor. [13].

Fig.2.6 Substrate particles (a) distantly located with more gaps before fermentation (b) compactly located with each other after fermentation.
Usually, air pressure drop across the inlet and outlet of the column increases with respect to the column height and time. It was found that pressure drop decreases at the end because a bed shrinkage forms a gaps between bed and wall of the column \cite{30,31}. Hence air can pass easily through this gap as shown in Fig.2.7 however; it does not contribute in a positive way as it is not judicious. Further, design considerations need to be understood the merits and demerits of each design which are discussed in the next section.

Fig.2.7: Gap formed between the wall and bed of the substrate in PBSSF.

Inset: Substrate particles with hyphae

### 2.4.3 Basic design for the head of PBSSF

In the old head design of PBSSF shown in Fig. 2.8, head surface is comparatively cooler due to condensation as a result of pressure drop at the head space of reactor. This is problematic, since the condensed water comes down and overflows or floods the top portion of the bed \cite{13}. To overcome this problem, the conceptual design shown in Fig. 2.9 is suggested where hemispherical head is replaced by conical head.
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Fig. 2.8: Old head design for PBSSF

Fig. 2.9: Improved head with weir and plate in PBSSF
Hemispherical head shown in Fig. 2.8 can withstand high pressure. But, PBSSF is not generating very high pressure; hence this head can be replaced by conical head shown in Fig. 2.9. Conical head can minimize flooding problem generated at the top of column. The high slope of conical head allows the condensate collected in side tray to be removed by side pipe minimizing the high moisture content or flooding problem at the upper layer of substrate in the bed.

Generally large capacity reactors have water jacket along the wall of column for temperature control, but it is not enough. Hence, small (one or more) perforated tube called as draft tube as shown in Fig. 2.10 is inserted along central axis of the column. This perforated tube provides better aeration and can remove more heat from central position\textsuperscript{[13]} by convection.

![Diagram of PBSSF with draft tube at central axis](image)

**Fig. 2.10** : PBSSF with draft tube at central axis

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2.4.4 Conical packed bed solid state fermentation system

The disadvantages of traditional packed bed solid state fermentor can be overcome by a novel conceptual design of conical packed bed solid state fermentor (CPBSSF) as shown in Fig. 2.11. Two extra air inlets are provided for upper region in CPBSSF. CPBSSF gives more surface area at the top. This high surface area increases the rate of heat transfer at the top portion of the column. Water evaporation rate at the top portion is also high. Even loading and unloading is comparatively easy in CPBSSF. CPBSSF provides such design that can reduce problems of pressure drop to certain level.

![Fig.2.11: Conical packed bed solid state fermenter (CPBSSF)](image-url)
2.5 Applications of PBSSF

Many products produced by PBSSF are summarized here (Table-2.1) along with substrates and culture used. Continuous research is going on packed bed column due to low product value at present date but is projected as future technology with high efficiency.

Table 2.1 Various products formed by PBSSF.

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>SSF Type</th>
<th>Specifications</th>
<th>Substrate</th>
<th>Culture used</th>
<th>Product</th>
<th>Reference No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Packed bed column</td>
<td>34.5 cm height &amp; 15 cm diameter</td>
<td>steamed wheat bran (1.3 Kg)</td>
<td>Aspergillus niger</td>
<td>Gluco-amylase</td>
<td>[15,16]</td>
</tr>
<tr>
<td>2</td>
<td>Zymotic packed bed column</td>
<td>Rectangular shaped bioreactor.</td>
<td>sugarcane bagasse &amp; wheat bran (13-40kg)</td>
<td>Trichoderma harzianum</td>
<td>Cellulase</td>
<td>[17]</td>
</tr>
<tr>
<td>3</td>
<td>Packed bed column</td>
<td>Column aeration only for the first 10 hr of operation.</td>
<td>Agrowaste 4.1 kg bed</td>
<td>Schwanniomyces castelli</td>
<td>Ethanol production</td>
<td>[18]</td>
</tr>
<tr>
<td>4</td>
<td>Packed bed column</td>
<td>Size 14.7cm Dia. &amp; 50cm Height</td>
<td>Sweet potato residue</td>
<td>Streptomyces rimosus</td>
<td>Oxytetracycline production</td>
<td>[19]</td>
</tr>
<tr>
<td>5</td>
<td>Packed bed column</td>
<td>Two steel cylindrical units. Each unit was of 2m length and 0.5m diameter</td>
<td>Chaff and wheat bran mixture</td>
<td>Trichoderma viride</td>
<td>Production of cellulase enzyme</td>
<td>[20]</td>
</tr>
<tr>
<td>6</td>
<td>Packed bed column</td>
<td>Two cylindrical reactors containing baskets of 40cm diameter and 50cm height.</td>
<td>Dry sugar beet (3kg)</td>
<td>Non fermentative</td>
<td>Sugar beet pulp</td>
<td>[21]</td>
</tr>
</tbody>
</table>
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<table>
<thead>
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<th>Product</th>
<th>Reference No</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Packed bed column</td>
<td>Size 9.5cm Dia. &amp; 25cm Height Imbibed with nutrients (1.5Kg)</td>
<td>Amberlite Imbibed with nutrients</td>
<td>Aspergillus niger</td>
<td>Citric acid</td>
<td>[22]</td>
</tr>
<tr>
<td>8</td>
<td>Packed bed glass-bioreactor</td>
<td>60 cm height and 5 cm diameter Wheat bran</td>
<td>Aspergillus niger</td>
<td>Biomass production</td>
<td></td>
<td>[23]</td>
</tr>
<tr>
<td>9</td>
<td>Packed bed column</td>
<td>20cm height and 4 cm diameter Buckwheat seed</td>
<td>Aspergillus niger</td>
<td>Production of spores</td>
<td></td>
<td>[24]</td>
</tr>
<tr>
<td>10</td>
<td>PBSSF</td>
<td>Cylindrical unit with a capacity of 4.4 litres having 25 cm long vertical cylinder with internal diameter of 15 cm JS Aspergillus oryzae</td>
<td>JS</td>
<td>Cellulase</td>
<td></td>
<td>[25]</td>
</tr>
</tbody>
</table>

Thus, it can be concluded that PBSSF is widely used for the production of large number of products with a wide range of substrate and therefore the research initiative needs further direction, analysis and inferences from newer experimentations, modeling and comparison. Some of the aspects have been attempted and deliberated in next chapters.
References:


