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An evaluation of different bioreactor configurations for continuous bio-ethanol production

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HIGHLIGHTS

- Two bioreactor configurations were constructed and compared.
- Continuous bioethanol production was performed in both bioreactors.
- Plate heat exchanger bioreactor was the best for solid mash fermentation.
- Operational power costs of both bioreactors were different in small scale levels.
- Further study needed for both bioreactors with optimized parameters.

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ABSTRACT

In this preliminary investigation, a so-called Blenke cascade and plate heat exchanger bioreactor configuration were compared in terms of mixing characteristics, contamination free process, operational power costs and overall performance. At room temperature, fermentation was initially started as batch run and switched to continuous operation, when the residual sugars within the reactor were detected to be $C \leqslant 1\%$ (g/L). Samples from both configurations were taken and analyzed for ethanol and residual sugar content, as well as for any infection of the fermentation and lactic acid content, respectively. Mixing characteristics were studied by the residence time distribution method. Both geometries behaved as a finite number n of continuous stirred tanks in series, behaving as a plug flow with superimposed axial dispersion. The number of tanks in series n obtained in the plate heat exchanger configuration was 1.5–3 times larger than those in the Blenke cascade. The average ethanol productivity was $Q_p = 3.07$ (g/L h) and $Q_p = 2.31$ (g/L h) for cascade and plate exchanger configuration, respectively. The analysis of operational power costs indicates relevant differences between the two reactors at laboratory scale; however, systems with different types of pumps and viscosities are compared. From an industrial scale point of view, specific operational costs decrease with scale-up, as no mechanical mixing is needed in the fermenters.

1. Introduction

The development of high-efficiency bioreactors is an important goal in present bioprocess research [1]. Many researchers have focused on methods for the improvement of continuous fermentation using different fermenter designs [2–10], different continuous fermentation bioreactors coupled with ethanol separation technologies [11–15], immobilized bacteria or yeast cells [16–18], different fermenting organisms [19] or a combined optimization system to use solar energy as support for the ethanol industry [20]. Although these reactor designs and fermentation techniques have resulted in some progress, the main drawbacks of the traditional ethanol production process such as high product inhibition, low energy efficiency, low productivity, high residence time and large amounts of wastewater discharge still prevail.

An efficient biocatalyst system must be available in a bioreactor configuration, which optimizes interphase contact, mass transport and conversion kinetics. The characteristics of an advanced bioreactor should include, if possible, a high concentration of the biocatalyst, continuous operation and excellent contact between the reacting components [21]. One way of achieving this, is by choosing and designing a reactor which tends to behave like a plug flow and provides an effective mass transport. The choice of PFR (Plug Flow Reactor) vs. CSTR (Continuous Stirred Tank Reactor) depends on conversion. It is preferable to choose a reactor with the smallest volume to reduce cost. PFR is always a smaller reactor for a given conversion, when kinetics are of positive order [22].

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Nomenclature

C_p	specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)	p_1	absolute inlet pressure (Pa)
C_v	specific heat at constant volume ($J\,kg^{-1}\,K^{-1}$)	p_2	absolute discharge pressure (Pa)
D	diameter of the bioreactor (m)	Q_p	volumetric ethanol productivity ($g\,L^{-1}\,h^{-1}$)
D_{eh}	equivalent hydraulic diameter (m)	R	gas constant for carbon dioxide ($J\,kg^{-1}\,K^{-1}$)
H	hydrostatic height (m)	t	apparent fermentation time (h).
H_{ad}	specific work ($N\,m\,kg^{-1}$)	T_1	inlet gas temperature (K)
L	bioreactor length (m)	T	temperature (K)
$\dot{m}$	mass flow rate of the gas in the reactor ($L\,s^{-1}$)	ΔP	pressure drop (Pa)
P	absolute pressure (Pa)	κ	ratio of specific heat at constant pressure to that at constant volume (adiabatic exponent) (–)
P_{ad}	power (W)		
P_{eth}	actual ethanol concentration produced ($g\,L^{-1}$)		

In the present work, ethanol fermentation using *Saccharomyces cerevisiae* was conducted in two different continuously operating bioreactors. The Blenke cascade fermenter configuration is a cylindrical bioreactor having inserts causing toroidal vortices, thus enhancing mixing. The other investigated configuration is a rectangular bioreactor having corrugated plates (plate heat exchanger fermenter configuration) to improve plug flow characteristics and an effective mass transport.

Different aspects can play a role in the choice of a reactor design, such as compactness, commercial availability, ease of heat transfer in the heat exchanger configuration or cleanability. Blenke cascade as cylindrical geometry and plate heat exchanger configuration as mainly rectangular duct with sinusoidal corrugations differ in some of these aspects. For example, regarding compactness, a plate heat exchanger has a much smaller distance between plates than the diameter of the cylindrical geometry, leading to a higher compactness. On the other hand, similar flow phenomena can be seen in these geometries. They show a flow separation in flow direction after inserts (Blenke cascade) or after the crest of the sine wave (plate heat exchanger). Both flow separations may contain vortices extending in spanwise direction, shown in Fig. 1d for the Blenke cascade. In both cases, this may influence the residence time distribution in the apparatus. Both, through their geometry, can have an early transition to turbulent flow compared to a rectangular duct. Therefore, the two designs were compared in terms of mixing characteristics, overall performance, operational power costs and contamination free process.

2. Materials and methods

For the purpose of comparison in these preliminary investigations, all fermentation processes were conducted at room temperature.

2.1. Materials

The feed was composed of 10 kg each of yeast and yeast extract per cubic meter of tap water. The carbon source was glucose and maltose from saccharification of $C = 25\%$ (kg/L) dried solid (wheat flour).

The yeast for the fermentation, *S. cerevisiae* (Kornbrand), reported to have a high temperature tolerance was obtained from Schliessmann Schwäbisch Hall, Germany and the yeast extract from Leiber GmbH, Germany.

2.2. Bioreactor configurations

2.2.1. Blenke cascade bioreactor configuration

The Blenke cascade is a special setup of gas lift reactor. The common gas lift reactor, being a straight column mostly, has large

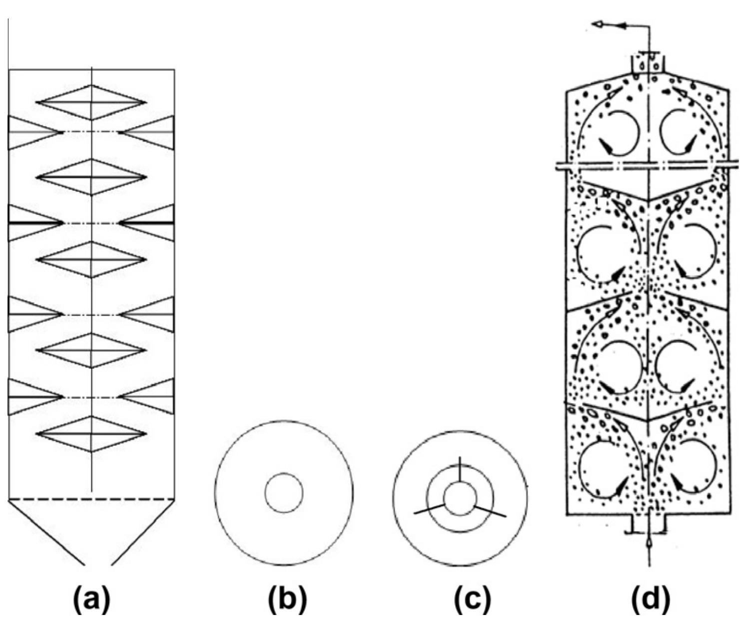

Fig. 1. Blenke cascade bioreactor configuration Cascade configuration (a), donut inserts (b), disc inserts (c) and flow behavior (d).