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Influence of dual-impeller type and configuration on oxygen transfer, power consumption, and shear rate in a stirred tank bioreactor

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ABSTRACT

In conventional stirred and aerated tank bioreactors, the choice of impeller type and configuration is critical to ensure suitable hydrodynamic conditions that maximize oxygen transfer while minimizing power consumption and shear rate. In this work, a systematic comparative evaluation of the performance of seven different dual-impeller configurations in a stirred tank bioreactor was carried out using Rushton turbines (RT) and Elephant Ear impellers in down-pumping (EEDP) and up-pumping (EEUP) modes. A 2^2 factorial design methodology was used to assess the effects of impeller speed (600–1000 rpm) and specific air flow rate (0.4–1.2 vvm) on the response variables. The EEDP-EEUP, RT-EEDP, and EEDP-RT combinations gave the best results in terms of oxygen transfer (k_La) and power consumption (P), with mass transfer efficiency ($E_{MT} = k_La/P$) up to 5.09 J^{-1}, which was 87% higher than for the RT-RT combination. For the selected impeller combinations (EEDP-EEUP, RT-EEDP, and RT-RT), the shear effects were quantified in terms of average shear rate ($\dot{\gamma}_{av}$) and using the Kolmogorov microscale (λ). The EEDP-EEUP dual-impeller combination proved to be the best system, with shear conditions ($2174 < \dot{\gamma}_{av}$ (s^{-1}) < 4287) up to 60% lower than for the conventional RT-RT configuration. The results indicated that the EEDP-EEUP system was most suitable for the growth of shear-sensitive aerobic microorganisms, ensuring adequate mass transfer and minimizing cell damage.

1. Introduction

The cultivation of filamentous aerobic microorganisms in stirred and aerated bioreactors is important in many industrial sectors, where this technology is used to manufacture products including enzymes, antibiotics, organic acids, proteins, and some aromatic compounds [1,2]. In order to optimize operating conditions and develop bioprocesses that maximize the production and yield of the desired products, it is necessary to achieve a balance between factors including pH, temperature, fermentation broth homogeneity, nutrients, oxygen transfer, and shear conditions. These parameters affect the morphology of filamentous fungi, bacteria, and animal cells [3–7], as well as the yield of the product of interest. Therefore, the relationship between microorganism morphology and product formation is an important and complex matter that needs to be investigated. Stirring of the culture broth is one of the key parameters that affect cellular fragmentation. Various bioreactor geometries with modified stirring systems have been proposed with the aim of causing less damage to filamentous microorganism cells [8–11]. However, there has been little attempt to study the design of the impellers used for mixing in terms of their effects on important performance parameters such as oxygen transfer, average shear rate, turbulent kinetic energy, and Kolmogorov scale, among others [12–15]. There have been even fewer studies concerning the use of different impeller combinations to increase productivity or to reduce enzyme deactivation during cultivation [16,17]. Selection of a suitable impeller type and configuration is extremely important in order to ensure satisfactory process conditions in conventional stirred tank bioreactors. The geometry of the impeller employed influences the hydrodynamics of the fermentation broth, power consumption, oxygen transfer, shearing, and morphology of the filamentous microorganisms, consequently affecting the biosynthesis of the product of interest [15]. Therefore, selection of an appropriate impeller requires accurate information about the fluid properties, operating conditions, and any other specific aspects of the system [18].

The commonest impeller used in conventional bioreactors is the Rushton turbine (RT), which imparts a radial flow to the broth. Although it provides an appropriate transfer of oxygen for the process, a disadvantage is that it generates non-uniform mixtures

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Nomenclature

b,c,d,e	parameters of Eqs. (5), (6), and (7) (−)
f,g,h,i	parameters of Eq. (8) (−)
x,y,w,z	parameters of Eq. (9) (−)
Ce	dissolved oxygen concentration (mmol L^{-1})
Ce_0	dissolved oxygen concentration at $t = t_0$ (mmol L^{-1})
Ce_S	saturation concentration of dissolved oxygen with air (mmol L^{-1})
RT	rushton impeller
EE	Elephant Ear impeller
EEUP	Elephant Ear impeller with up-pumping
EEDP	Elephant Ear impeller with down-pumping
SG	glycerol solution
XGS	xanthan gum solution
br	distance between the motor shaft and the dynamometer (m)
E_{MT}	efficiency of mass transfer (J^{-1})
F	force (N)
K	consistency index (Pa s^n)
k_e	electrode sensitivity (s^{-1})
k_La	coefficient of oxygen transfer (s^{-1})
N	Impeller speed (rpm)
n	flow behavior index (−)
P	power consumption (W)
T	torque (N m)
V	working volume (m^3)
Greek letters	
ϕ_{air}	specific air flow rate (vvm)
$\dot{\gamma}$	shear rate (s^{-1})
$\dot{\gamma}_{av}$	average shear rate (s^{-1})
ε	energy dissipation rate (W kg^{-1})
λ	kolmogorov's microscale (μm)
μ	dynamic viscosity (Pa s)
μ_{ap}	apparent dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2 s^{-1})
ρ	specific mass (kg m^{-3})
τ	shear stress (Pa)
τ_e	response time (s)
ω	angular velocity (rad s^{-1})

with a high degree of shear near the tips of the blades and mild shear at the periphery of the bioreactor, and also has high power consumption [8,19]. More recently, impellers with axial or mixed (axial/radial) flows have been studied, which provide more effective circulation within the reactor and generate lower shear stress, compared to radial flow impellers [13]. A new type of impeller, known as Elephant Ear (EE) due to the shape and positioning of the blades, has become widely studied in bioprocess development, because it offers characteristics such as low shear and satisfactory oxygen transfer. This type of impeller is usually employed in cultures that generate viscous broths containing organisms sensitive to shear, such as animal cells, plant cells, bacteria, and filamentous fungi [20]. Elephant Ear impellers possess three inclined flat blades and generate a mixed fluid flow (axial and radial) that provides better overall mixing, leading to a higher oxygen transfer coefficient (k_La), compared to (for example) impellers with one-way marine-type blades. Due to the characteristics of axial flow, EE impellers can impart up-pumping (EEUP) or down-pumping (EEDP) flows, depending on the orientation of the blades and the direction of rotation (clockwise or anticlockwise) [20]. Therefore, studies focusing on the potential of using EE impellers in microbial cultivation systems, together with the ways in which this type of impeller and the selected configuration influence bioprocess performance, are of great importance for the improvement of future large-scale operations.

In bioreactors, cell fragmentation occurs when the local shear stress exceeds the tensile strength of the hyphae, which can become as long as 100–300 μm during fungal cultivations [21]. Studies suggest that the most plausible mechanisms of cell fragmentation are those based on interaction between the cells and eddies formed due to the bioreactor operating conditions (stirring and aeration) [2]. Kolmogorov's theory of isotropic turbulence [22] has been employed as a basis for estimating the shearing of cells, using Kolmogorov's microscale (λ), which refers to the size of the smallest eddy formed inside the bioreactor [2]. This reflects the fact that the mechanism responsible for fragmentation of the hyphae of fungi or bacteria depends on the relationship between the size of the hyphae and the microscale length [21]. Eddies in the range 10–50 μm are smaller than the hyphae of filamentous microorganisms, leading to increased cell-eddy interaction and greater cell damage due to shearing. On the other hand, larger eddies generally transport the cells along the flow lines, resulting in less damage [2,21,23]. Fig. 1 provides a schematic illustration of the influence of eddy size on the shearing of cells, together with the stages of shear, during which the pellets are transformed into clumps and then into isolated and ramified hyphae.

In bioprocesses, oxygen mass transfer and shear conditions are closely related. Tanaka et al. [24,25] studied this relationship in detail, showing how the operating conditions and mixing apparatus, considering bioreactor and impeller type, affected the oxygen mass transfer and shear rate for plant cells. In other work, Tanaka [26] associated the shear rate with oxygen mass transfer using the viewpoint that the same factors influence both parameters. This enabled development of a method for quantitative determination of the intensity of hydrodynamic stress, a parameter that is difficult to measure directly. Recently, Cerri et al. [27] proposed an alternative method to quantify the average shear rate ($\dot{\gamma}_{av}$) in airlift bioreactors, using k_La as a characteristic parameter. Given the critical relationships among the operating conditions that affect mixing and oxygen transfer, and the potential impact of shear stress on the growth and morphology of the filamentous microorganisms, it is important to understand how the impeller type and configuration affect the performance of bioprocesses.

Therefore, the aim of this study was to evaluate different dual-impeller configurations with Rushton turbine and Elephant Ear impellers (in down-pumping and up-pumping modes), with determination of the overall oxygen transfer coefficient (k_La), average shear rate ($\dot{\gamma}_{av}$), and eddy size, using the Kolmogorov microscale (λ), in a bench-scale stirred tank bioreactor.

2. Materials and methods

2.1. Fluids

Glycerol solutions (GS) were used as Newtonian fluids and xanthan gum solutions (XGS) were used as non-Newtonian fluids. The dynamic viscosity (μ) of the Newtonian fluids and **t**he power law rheological parameters (consistency index, K; flow index, n) were determined from rheograms obtained using a digital concentric-cylinder rheometer with SC4-31 and SC4-18 spindles (LV-DVIII+, Brookfield Engineering Laboratories Inc.), at 32 °C. Table 1 gives the rheological properties of the fluids used in this study.

2.2. Bioreactor and impellers

The power consumption tests were carried out using the experimental apparatus proposed by Corrêa et al. [28] and adapted for this