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Hydrodynamic effect of dispersed phase fraction on the mass transfer and uptake rate of hexadecane by an oil-degrading microbial consortium in an airlift bioreactor

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ABSTRACT

An investigation was made into the hydrodynamics related to mass transfer of the oil and gaseous phase in an airlift reactor (ALR), using a high dispersed phase fraction ($\varphi = 0.1$) for biodegradation purposes, in a simulated biotic medium. The highest Reynolds differences ($3400 < Re < 5400$) and low liquid velocity differences between the aqueous and oil phase ($0.02–0.05\ m\ s^{-1}$) were obtained in the riser at assayed superficial gas velocity (*Ug*). The hexadecane (HXD) specific mass transfer area was increased due to the presence of a greater HXD volume, which enhanced the volumetric hexadecane gas-liquid mass transfer coefficient ($k_L a_{HXD}$) compared to other works at $\varphi < 0.1$. Thus, high HXD transfer rates were obtained through a 14-day batch culture. Conversely, the high φ value promoted a volumetric oxygen gas-liquid mass transfer coefficient ($k_L a_{O2}$) enhancement. The oxygen transfer rates were improved because of an increase in the oxygen saturation concentration. The maximum uptake rates obtained were 3.44–7.74 g HXD $L^{-1}\ h^{-1}$. The increase in *Ug* with a high φ value, led to a positive effect that improved the mass transfer of HXD and oxygen, allowing high HXD uptake rates.

1. Introduction

Airlift reactors (ALRs) are cylindrical vessels containing a split or a draft tube, establishing two characteristic zones: riser and downcomer. Typically, the gas-phase is injected into the riser, and the density difference causes the driving force for recirculation [1], providing a low uniform shear stress and low energy consumption over other conventional reactors, like stirred tanks or bubble columns [2]. ALRs are widely used devices for industrial biotechnological applications, like wastewater treatment, biomass and high-value chemicals production, biodesulfurization processes and hydrocarbon bioremediation [3,4]. In the studies of hydrocarbon bioremediation with ALRs, hexadecane (HXD) has been used as a model molecule because alkanes are a major component of the oil and diesel [5] and have a well-characterised biodegradability [6].

Scarce information is available about the mass transfer from oil to an aqueous phase, for improving biodegrading processes in ALRs. Most studies of hydrocarbon biodegradation in bioreactors using a consortium of hydrocarbon-degrading microorganisms, have used low hydrocarbon concentrations of $1–20\ g\ L^{-1}$ (which can be called a low dispersed phase fraction, φ) [7,8]. Regarding biomass production and hydrocarbon biodegradation in ALR, studies with different hydrocarbons and low φ, have been conducted to investigate the mass transfer parameters related to their hydrodynamics [9,10]. Notwithstanding these authors only consider the gas phase.

The mass transfer coefficient (k_L) describes the efficiency with which mass, oxygen or non-soluble substrate, can be delivered to a bioreactor under a given set of operating conditions. Several studies propose that an increase in the alkane concentration can lead to a higher resistance to oxygen mass transfer, due to the viscosity increase [11–13]. Thus, the volumetric oxygen gas-liquid mass transfer coefficient ($k_L a_{O2}$) decreases [14], which can produce low hydrocarbon uptake rates and low biomass yields, used for bioremediation purposes [15]. However, other works suggest an enhancement of $k_L a_{O2}$ due to the presence of an oil phase. The reason for this is that alkanes can diminish the surface tension (σ) and, consequently, prevent coalescence of bubbles, increasing the interfacial area per unit volume. With the addition of alkanes to the culture medium, an increase in the oxygen saturation concentration is observed [7], because of the high solubility of oxygen

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Nomenclature

ALR	Airlift reactor (−)
A_r	Cross-sectional area of riser (cm^2)
A_d	Cross-sectional area of downcomer (cm^2)
C_e	Actual electrode-measured dissolved oxygen concentration ($g\,L^{-1}$)
C^*_{HXD}	Saturation concentration of HXD in aqueous phase ($g\,L^{-1}$)
C_{LHXD}	HXD concentration in aqueous phase a time t ($g\,L^{-1}$)
C^*_{O2}	Saturation concentration of oxygen in aqueous phase ($g\,L^{-1}$)
C_{LO2}	Oxygen concentration in aqueous phase at time t ($g\,L^{-1}$)
d_{32}	Sauter mean diameter (cm)
HXD	Hexadecane (−)
HTR	Hexadecane transfer rate ($g\,L^{-1}\,h^{-1}$)
k_e	Electrode time constant (h^{-1})
k_{LHXD}	HXD mass transfer coefficient ($cm\,h^{-1}$)
k_La_{O2}	Volumetric oxygen mass transfer coefficient (h^{-1})
k_La_{HXD}	Volumetric HXD mass transfer coefficient (h^{-1})
m_{oxygen}	Oxygen mole fraction (−)
OTR	Oxygen transfer rate ($g\,L^{-1}\,h^{-1}$)
r_{max}	Maximum HXD consumption rate (g HXD $L^{-1}\,h^{-1}$)
R	Universal gas constant ($J\,mol^{-1}\,K^{-1}$)
Re	Reynolds differences between aqueous and oil phase (−)
SS	Suspended solids ($g\,L^{-1}$)
T	Temperature (K)
Ug	Superficial gas velocity ($cm\,s^{-1}$)
V_{Aq}	Aqueous phase velocity ($m\,s^{-1}$)
V_{HXD}	HXD phase velocity ($m\,s^{-1}$)
V_L	Volume of the emulsion (m^3)
V_L	Volume of the gas phase (m^3)
X	Fractional conversion of HXD (−)

Greek symbols

μ	Dynamic viscosity ($kg\,m\,s^{-1}$)
ρ_{Aq}	Aqueous phase density ($kg\,m^{-3}$)
ρ_{HXD}	HXD phase density ($kg\,m^{-3}$)
σ	Surface tension ($dynes\,cm^{-1}$)
φ	Dispersed-phase fraction (−)

in the immiscible substrate, which increases the driving force for mass transfer. Therefore, high oxygen transfer rates (OTR) can be achieved.

However, due to the low solubility of hydrocarbons in water, few attempts have been made to research the oil phase hydrodynamics in airlift bioreactors at high φ [16]. Lizardi-Jiménez et al. [17], working with a hydrocarbon-degrading consortium, reported that the limiting step in the uptake of alkanes could be the mass transport phenomena from the oil to the aqueous phase, by emulsification and free macroscopic oil droplets [7]. Mass transfer studies are needed to enhance the biodegradation rates of hydrocarbons in ALRs. Mixing, agitation, and mass transfer rates depend on the superficial gas velocity (*Ug*), temperature, liquid physical properties, reactor configuration, and the hydrocarbon concentration [18]. Particularly, the mass transport of hydrocarbons at the interface depends on the Sauter mean drop diameter (d_{32}). Therefore, if a constant d_{32} is maintained and the dispersed-phase fraction is increased, it is possible to obtain a higher specific area for HXD mass transfer. At the same time, d_{32} is related to the Reynolds number (*Re*) and liquid velocity [19]. A high specific area is provided, by increasing the local turbulence. Therefore, a higher volumetric hexadecane liquid-liquid mass transfer coefficient (k_La_{HXD}), a novel mass transfer parameter to describe non-soluble substrate transfer, is obtained. In this way, the hydrocarbon transfer rate can be increased. Consequently, the bioavailability of immiscible substrates can be improved. Although it is possible to increase both k_La_{O2} and k_La_{HXD} by increasing the aeration rates, this can result in increased operational costs and energy consumption and can generate a hydrodynamic shear stress to sensitive cells [20]. However, in biodegradation processes in pneumatic reactors [21,22], the increase in the specific mass transfer area is an important factor of consideration for the successful operation. The use of high hydrocarbon loadings (which can be called high-dispersed phase fractions) on ALR operation could be a suitable method to enhance the hydrocarbon uptake rates.

This work determined the effect of the hydrodynamics on the oxygen and HXD mass transfer parameters and HXD uptake rate, in an ALR with an oil-degrading microbial consortium, in the presence of a high dispersed-phase fraction of HXD.

2. Materials and methods

2.1. Airlift bioreactor description

A 3-L airlift bioreactor of Pyrex glass with 0.08 m diameter and 0.68 m height was used. The concentric tube (0.35 m height and 0.05 m diameter) was collocated 0.035 m above the base. The ratio of the riser and downcomer cross-sectional area (A_r/A_d) was 1.56. Air was injected into the concentric tube, through a perforated L-shaped steel pipe with 0.005 m internal diameter and seven perforations of 0.001 m diameter and 0.004 m separation. The *Ug* was evaluated in the range of 1.5 – 3.5 $cm\,s^{-1}$. The ALR was operated with a 2.2-L working volume. The surface tension of the culture medium was measured with a bubble pressure tensiometer (SensaDyne, Chem-Dyne Research Corp., USA) at 25 °C. Pure water (72.7 $dynes\,cm^{-1}$) and ethyl alcohol (22.3 $dynes\,cm^{-1}$) were used as the references. Twenty millilitres of culture medium were put into a 50-mL glass beaker and placed onto the tensiometer platform. The surface tension value was expressed as the average of two readings from the same culture.

2.2. Microbial consortium and mineral medium

An identified microbial consortium, isolated from the rhizosphere of *Cyperus laxus*, a plant able to grow in an oil-contaminated marsh in Mexico [17], was used. The consortium was composed of four bacterial species: *Acinetobacter bouvetii*, *Shewanella* sp., *Defluvibacter lusatiensis* and *Xanthomonas* sp. Culture assays were conducted, using a mineral medium [15] consisting of (g/L): 6.75 $NaNO_3$, 2.15 K_2HPO_4, 1.13 KCl and 1.10 $MgSO_4{\cdot}5H_2O$. The mineral medium was combined with 77 $g\,L^{-1}$ HXD (reagent grade 99%; Sigma Aldrich, MO, USA) as the sole carbon and energy source. The final pH was adjusted to 6.5. Afterwards, the microbial consortium was cultured and grown in sequential batches for 14 days. Biomass was harvested (7 mL sample) by centrifugation at 4300*g* for 5 min. Cell pellets were washed three times with an isotonic solution (0.9% m/V, NaCl) to remove the residual HXD. The organic phases, including residual HXD, were pooled and stored at 4 °C in 30-mL vials. Initial conditions were restored, by adding 1 $g\,L^{-1}$ (wet weight) of the suspended solids (SS) from the previous batch culture.

2.3. Aqueous and HXD hydrodynamics

Aqueous (V_{Aq}) and HXD (V_{HXD}) fluid velocities were evaluated through a method published elsewhere [16]. Briefly, sodium polyacrylate hydrogel and oligosiloxane-stained spheres (0.005 m