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Characterization and hydrodynamics of a novel helix airlift reactor

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ABSTRACT

A novel pilot scale helix airlift reactor (helix-ALR) consisting of a regular draft tube airlift reactor ($A_d/A_r = 1.17$) and helical tubes attached to riser or downcomer, or both, was studied in different configurations with varying air inputs. The helical tubes acted as helical flow promoters (HFP) and additional gas spargers. The aim was to investigate the performance of these HFP-gas spargers and study their effect on oxygen transfer in ALR. HFP-gas spargers improved the volumetric oxygen transfer coefficients of the ALR radically even without additional energy, reaching up to 3 times higher k_La-values (over 0.1 l/s) when compared to regular ALR. Small bubbles from the HFP-gas spargers played an important role in the oxygen transfer, and downcomer helix had greater effect in general on k_La and hydrodynamics than riser helix. Empirical correlations regarding mass transfer and gas holdups were formed. When compared to stirred tank reactors (STR) the required specific power input of the helix-ALR for a level of k_La 0.1 l/s was around 0.34 kW/m^3 while for STR 2.0 kW/m^3, suggesting that the helix-ALR is very energy efficient. HFP-gas spargers can significantly improve the performance of ALRs regarding oxygen transfer, lower their operating costs and improve the total energy economy.

1. Introduction

Airlift reactors are pneumatic reactors modified from basic bubble columns. There are several different variations of ALRs (internal, external, cylindrical, rectangular, draft tube, baffle, etc.), but the working principle is the same in all of them: gas, usually air, is pumped to the riser part of the reactor which makes the fluid circulate in the reactor as the fluid bulk densities are different in the different parts of the reactor. The benefits of ALRs include efficient mass, oxygen and heat transfer, more even mixing and lower shearing forces as there is no need for separate mechanical stirrer, smaller operating costs and energy input, and simpler and more aseptic structure with less or no moving parts. ALRs are employed in various biological and chemical applications because of their advantageous character [1–4]. These include for example biological wastewater treatment (denitrifying, dephosphatation, phenolic treatment and waste gas treatment), oxidation and chlorination processes, microbial fermentations and production of biomass and metabolites [1,5–9]. A well-known industrial application of ALR is Quorn production in UK [10,11]. Also, the biggest ever built bioreactor was actually ALR which was used in the 80 s for the production of single cell protein (Pruteen plant) [12].

As potential they are, it is however, possible to enhance the performance of ALRs even more with additional parts or add-ons like HFPs. HFP was introduced by Merchuk et al. [13] but it hasn't got much attention in the literature. HFP – helical flow promoter – is a device (a flow guide) that causes the liquid to flow in a helical or a spiral pattern, and is usually located at the top of the riser or in the upper part of the downcomer, though, it can be installed in any part of the ALR. HFPs can improve mass transfer and especially fluidization of solid particles as well as radial mixing in the reactor [13–16]. By combining features of HFPs and gas spargers it may be possible to improve the mass transfer, mixing and overall performance of ALRs even further. In addition to HFPs, also other add-ons have been studied in ALRs to improve their performance, such as mechanical stirrers [17,18], self-agitators [19], baffles [9] and orificed baffles [20], modified risers [21], pumps [22,23] etc.

Oxygen transfer is often the rate-limiting step in aerobic bioprocesses due to the low solubility of oxygen in water, so it is important to know the parameters affecting it [24]. Such parameters include gas holdup and volumetric oxygen mass transfer coefficient (k_La). Gas holdup is the most widely researched

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Abbreviations: Adj.R^2, adjusted R^2; *ALR*, airlift reactor; *DO*, dissolved oxygen; *DT-ALR*, draft tube airlift reactor; *HFP*, helical flow promoter; *lpm*, liters per minute, gas flow rate; *Nlpm*, normal liters per minute (1 atm, 20 °C), gas flow rate; *STR*, stirred-tank reactor; *slpm*, standard liters per minute (1 atm 25 °C), gas flow rate.

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Nomenclature

A_r	Riser cross-sectional area (m^2)
A_d	Downcomer cross-sectional area (m^2)
A_d/A_r	Ratio of downcomer and riser cross-sectional areas
b_{cl}	Bottom clearance (m)
D_{di}	Downcomer equivalent inner diameter (m)
D_i	Reactor inner diameter (m)
D_L	Liquid phase diffusivity (m^2/s)
D_o	Reactor outer diameter (m)
D_{ri}	Riser (draft tube) inner diameter (m)
D_{ro}	Riser (draft tube) outer diameter (m)
Fr	Froude number (–)
Fr_r	Froude number based on riser (–)
$Fr_{r,avg}$	Average froude number based on riser used in setups 8–12 (–)
Fr_d	Froude number based on downcomer (–)
$Fr_{d,avg}$	Average froude number based on downcomer used in setups 8–12 (–)
g	Gravitational acceleration (m/s^2); 9.81 m/s^2
h	Reactor height (m)
h_D	Aerated liquid level (dispersion height) (m)
h_L	Non-aerated liquid level (static height) (m)
h_r	Riser (draft tube) height (m)
J_{gs}	Total superficial gas velocity (m/s) based on reactor cross-sectional area
J_{gsd}	Downcomer superficial gas velocity (m/s) through downcomer helix
J_{gsr}	Total riser superficial gas velocity (m/s)
J_{gsr1}	Riser superficial gas velocity (m/s) through gas sparger
J_{gsr2}	Riser superficial gas velocity (m/s) through riser helix
k_La	Volumetric oxygen mass transfer coefficient (l/s)
P/V	Specific power input (W/m^3)
R^2	Coefficient of determination
Sh	Sherwood number (–)
t_{cl}	Top clearance (m)

Greek letters

Δh_M	Distance between manometer levels in Eqs. (2) and (3) (m)
$\Delta\hat{z}$	Vertical distance between measurement points (pressure taps) in Eqs. (2) and (3) (m)
ε	Overall gas holdup (–)
ε_D	Downcomer gas holdup (–)
ε_R	Riser gas holdup (–)
ρ_g	Density of the gas (kg/m^3)
ρ_L	Density of the liquid (kg/m^3)
τ_e	Electrode response time (63.2%) (s)
τ_d	Electrode delay time (dead time, lag time) (s)

hydrodynamic property because of its importance in design exercises and direct effect to mass transfer through a combination of gas residence time and bubble sizes [25]. The correct measurement and/or prediction of the volumetric mass transfer coefficient also plays a crucial role in the design, operation and scale-up of bioreactors and ALRs [24]. These parameters give valuable information about the gas-liquid interactions and capacity of the reactor to transfer oxygen to the system and thus affect the overall performance of the reactors. Thus, when studying new reactor geometries and configurations it is important to characterize these parameters and be able to predict them for understanding and describing the system in a more comprehensive manner.

This paper describes an introduction of a new type of device or devices, which combine features of HFPs and gas spargers, into a pilot scale draft tube airlift reactor, and different configurations with these HFP-gas spargers. The local hydrodynamics regarding gas holdup and oxygen mass transfer are studied and empirical correlations formed to predict the hydrodynamics in different parts of the reactor.

2. Materials and methods

2.1. Airlift reactor

A cylindrical, pilot-scale draft tube ALR was built (Fig. 1).The dimensions of the reactor are shown in Table 1. All parts of the reactor were made of polymethyl methacrylate (PMMA; plexiglass) to allow easy visualization of the flow patterns inside the reactor. Draft tube was kept in place by two supporting legs at the bottom edge of the draft tube and six supporting legs around the side of the draft tube at two different heights. Draft tube bottom and top clearances (b_{cl}, t_{cl}) were 5 and 10 cm, respectively. Gas sparger was a cross shaped sparger made of POM (polyoxymethylene) which consisted of a round middle part (Ø 50 mm) which connected four perforated POM-tubes, which each had ten holes (Ø 0.5 mm), on two rows on the upper side of them, thus the sparger having 80 holes in total. Diameter of the gas sparger was 140 mm and it was located inside the draft tube 10 cm from the bottom edge of the draft tube. Airflow through the gas sparger was controlled with a verificated rotameter (VE-3KR, Kytola Oy, Finland) and varied between 50 and 110 Nlpm (normal liters per minute; 1 atm, 20 °C), as superficial gas velocity J_{gs} between 0.013–0.029 m/s. The regular ALR without any additional parts served as a configuration 1 (Table 2).

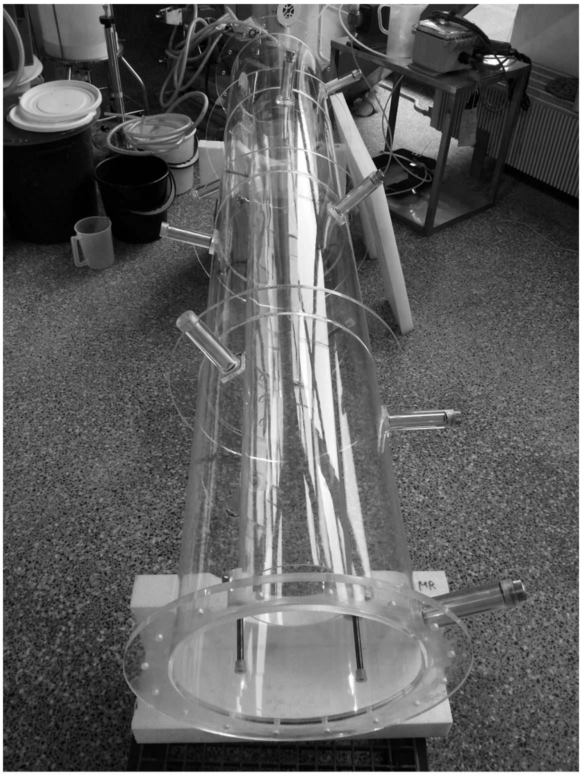

Fig. 1. Acrylic cylindrical draft tube airlift reactor.